PS review
June 7, 2004

γ-Ray Spectroscopy of Λ Hypernuclei
E419, E509, E518

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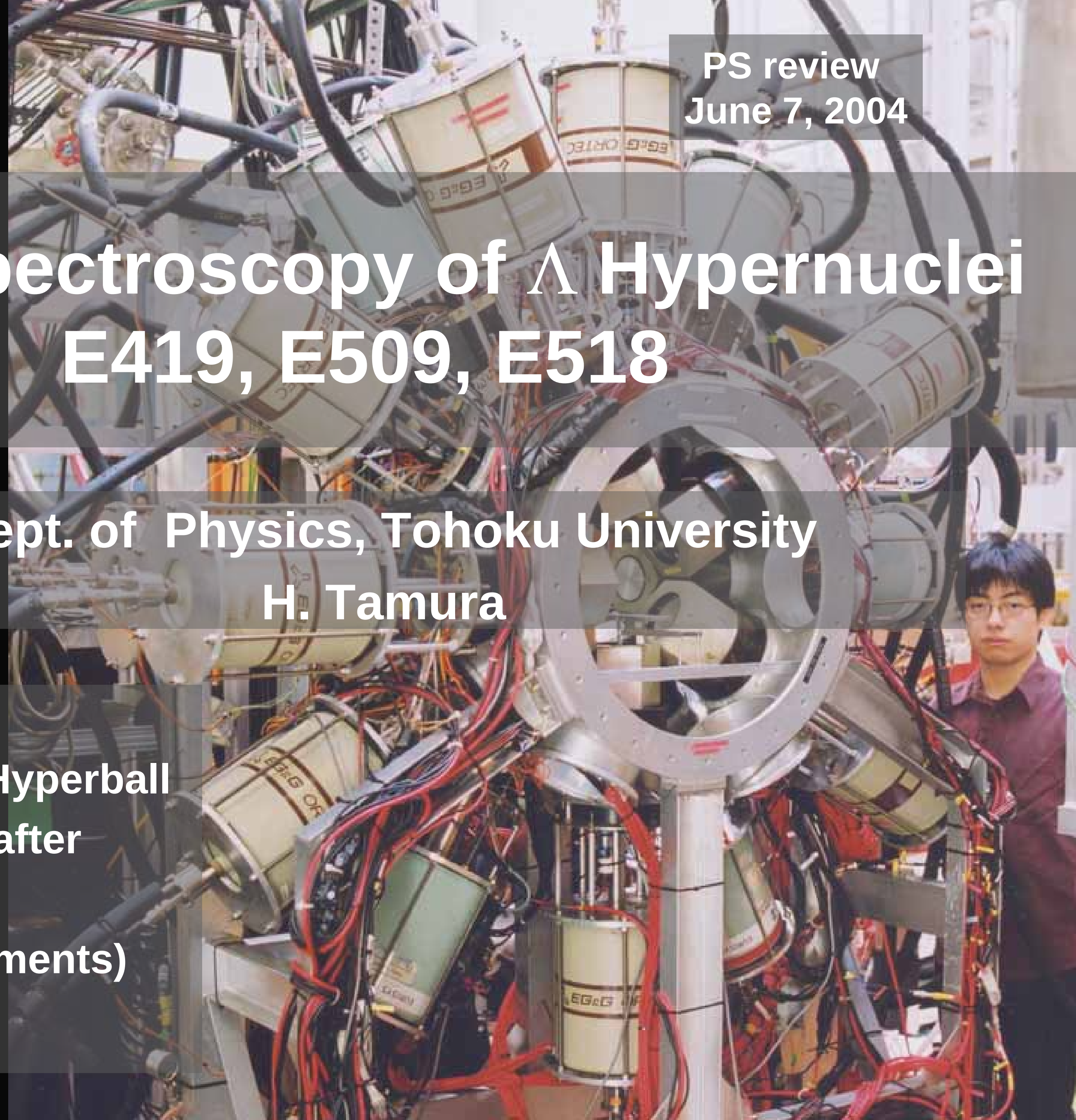
H. Tamura



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2. E419 ($^{7}_{\Lambda}$Li) and after
3. E518 ($^{11}_{\Lambda}$B)
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History of Precision γ Spectroscopy of Λ Hypernuclei

'96-'98	Construction of Hyperball
'98 Apr-May	KEK-E419 (K6/SKS) : $^{7}_{\Lambda}$Li
'98 Dec	BNL-E930 (D6) : $^{9}_{\Lambda}$Be
'01 Sep-Nov	BNL-E930 (D6) : $^{16}_{\Lambda}$O / $^{15}_{\Lambda}$N, $^{10}_{\Lambda}$B, etc.
'02 Apr	KEK-E509 (K5) : hyperfragments ($^{7}_{\Lambda}$Li)
'02 Sep-Oct	KEK-E518 (K6) : $^{11}_{\Lambda}$B

Future: before J-PARC

(KEK, to be proposed) $^{12}_{\Lambda}$C/ $^{11}_{\Lambda}$B, $^{4}_{\Lambda}$He

(BNL E930, E964)

Future: at J-PARC

Hyperball collaboration at KEK
E419, E509, E518 (1998, 2001,2002)

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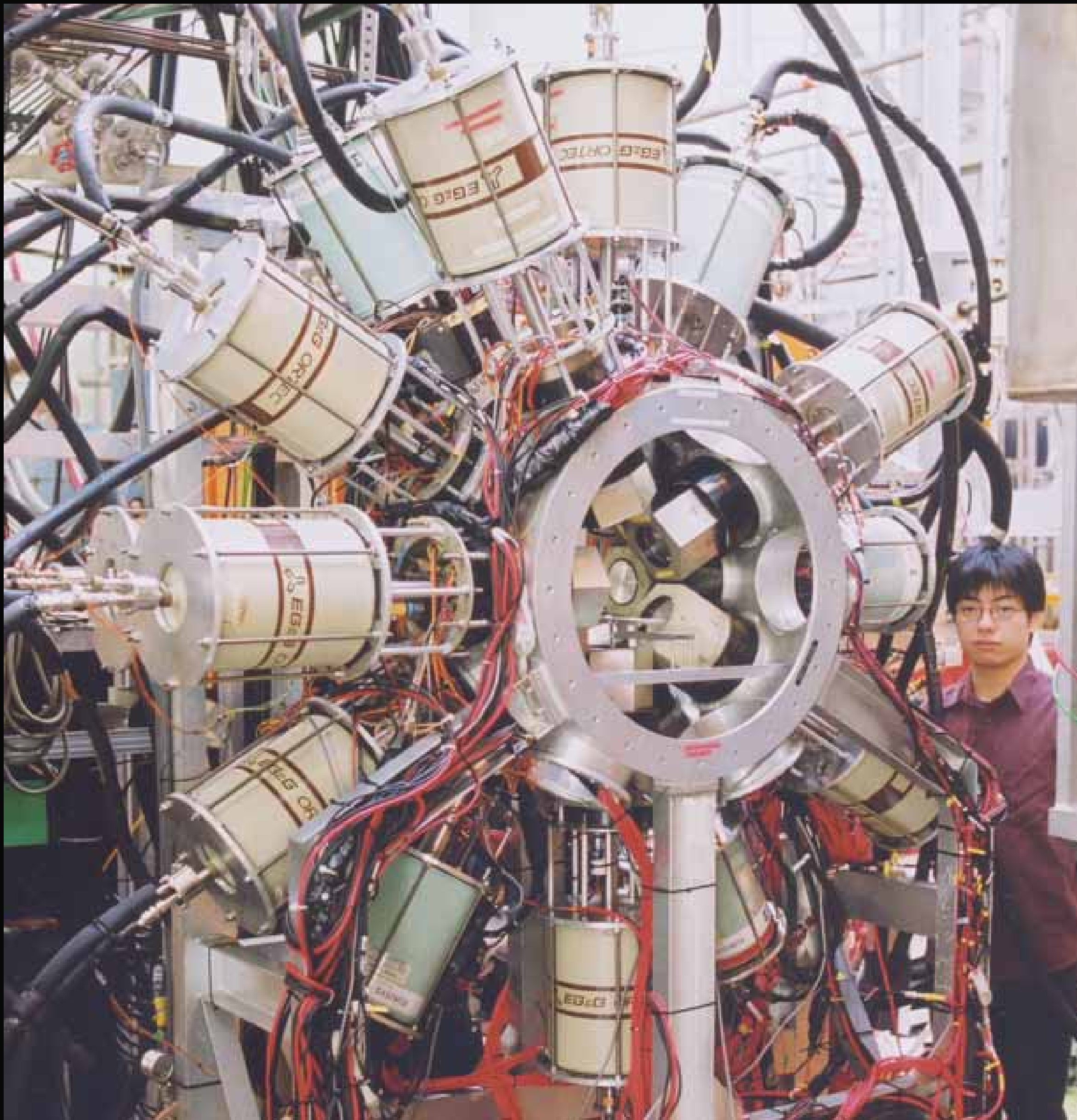
ITEP	**A. Krutenkova**

Hyperball (Tohoku/ Kyoto/ KEK, 1998)

- Large acceptance for small hypernuclear γ yields
  - Ge (r.e. 60%) x 14
  - Ω ~ 15%
  - ε_{peak} ~ 3% at 1 MeV
- High-rate electronics for huge background
  - 1 TeV/sec, 100 kHz
- BGO counters for π^0 and Compton suppression

Resolution of hypernuclear spectroscopy

1 MeV -> 2 keV FWHM



Motivations of hypernuclear γ spectroscopy

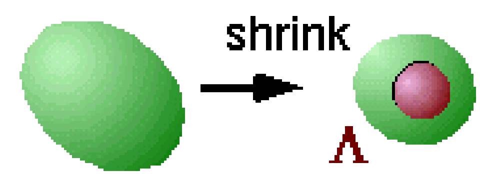
- **Baryon-baryon interactions** E419, E518

  Λ hypernuclear structure ⇆ *ΛN int. (meson or quark models)*

  c.f. *nuclear structure* ← *NN int. (phenomenologically known)*

  Unified understanding of B-B interactions

- **Impurity effects** E419

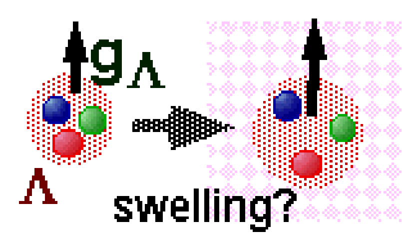
  

  Change of size and shape (shrinkage),

  New symmetries, Change of collective motions,...

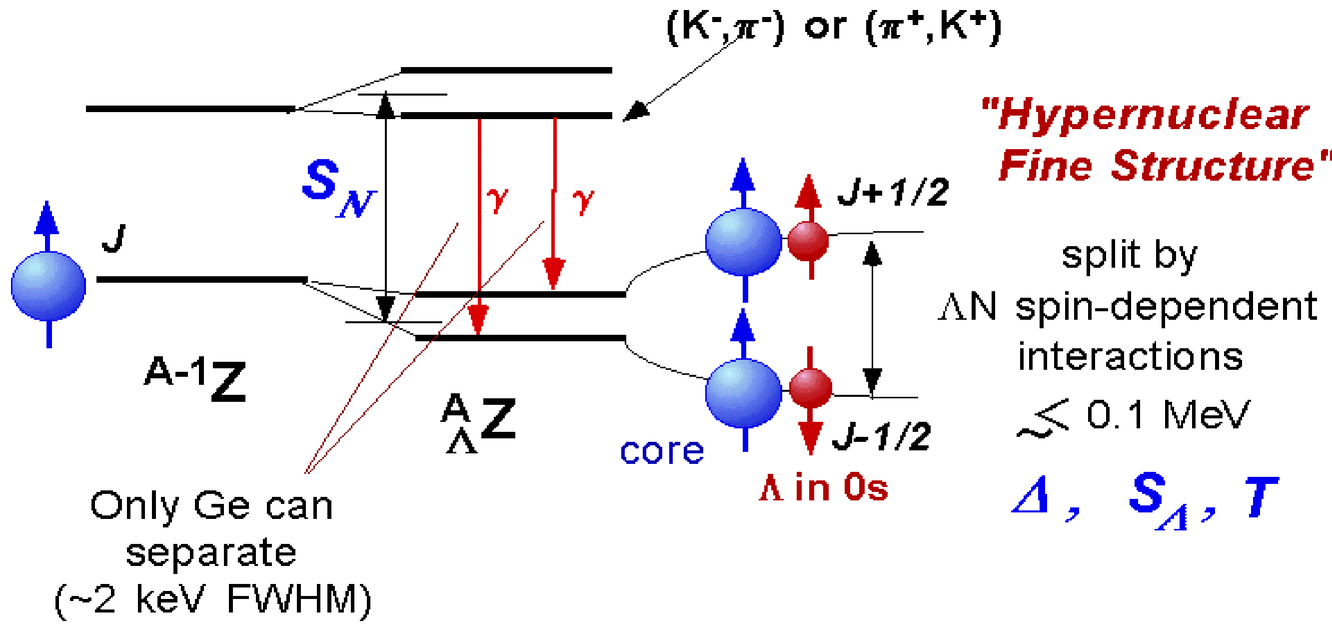
- **Medium effects** probed by hyperons free from Pauli

  Λ-spin-flip B(M1) → $\boldsymbol{g_\Lambda}$ E518

γ spectroscopy and ΛN spin-dependent interactions

- **Low-lying levels of Λ hypernucleus**



- **2-body ΛN effective interaction**

Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

$$V_{\Lambda N}^{eff} = V_0(r) + \underbrace{V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N}_{\Delta} + \underbrace{V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda}_{S_\Lambda} + \underbrace{V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N}_{S_N} + \underbrace{V_T(r)\, S_{12}}_{T}$$

p-shell : 4 radial integrals for $p_N s_\Lambda$ w.f.

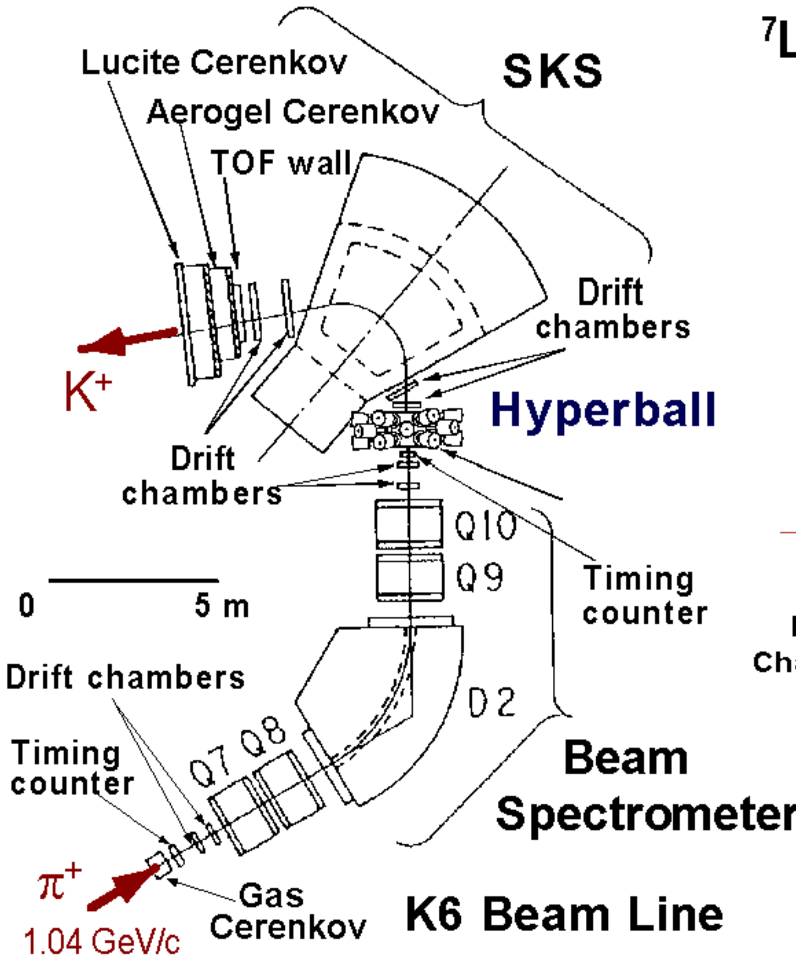
E419: γ-spectroscopy of $^{7}_{\Lambda}$Li

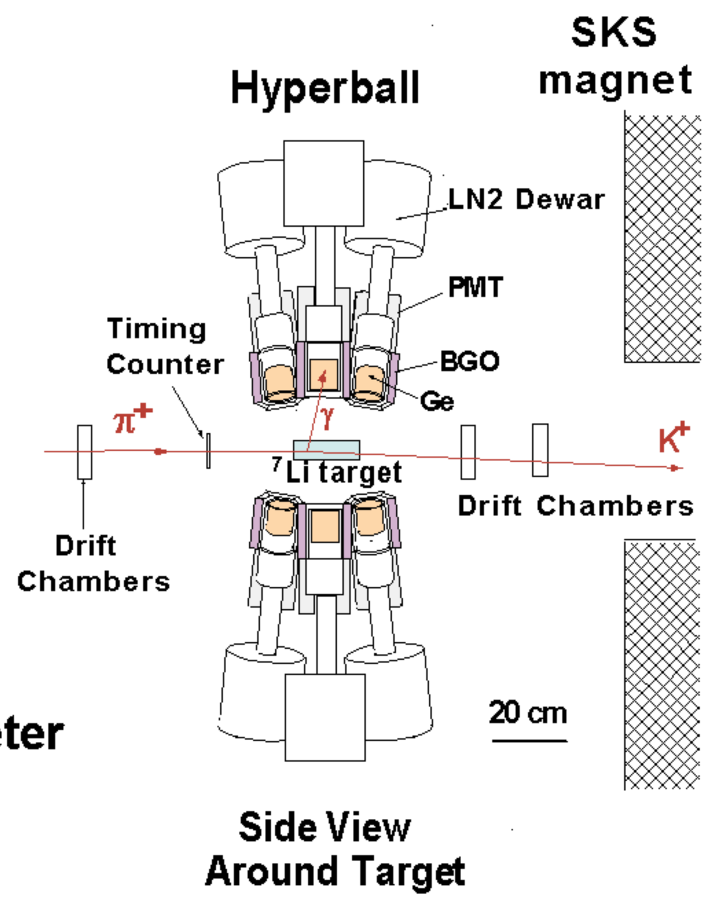
Run in April-May, 1998, at K6, 80 shifts

- First exp. with Hyperball
- B(E2) -> shrinking effect
- Spin-flip M1 -> ΛN spin-spin force

Setup for E419 (E518)

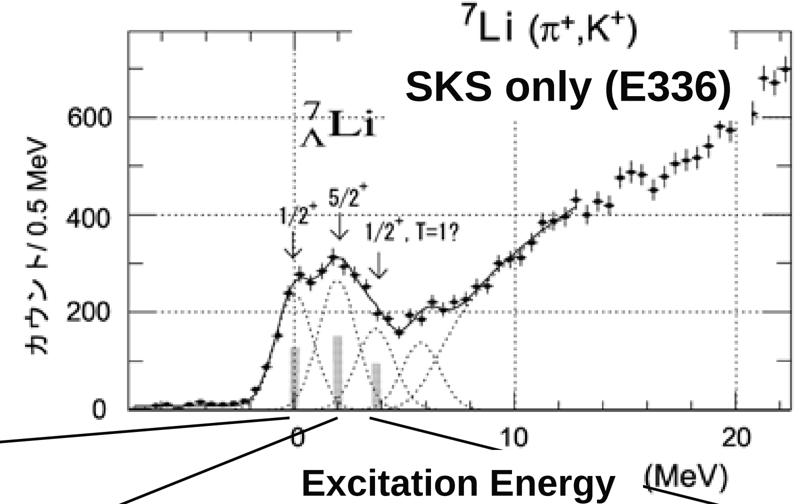
^{7}Li (π^{+}, $K^{+}\gamma$) $^{7}_{\Lambda}$Li

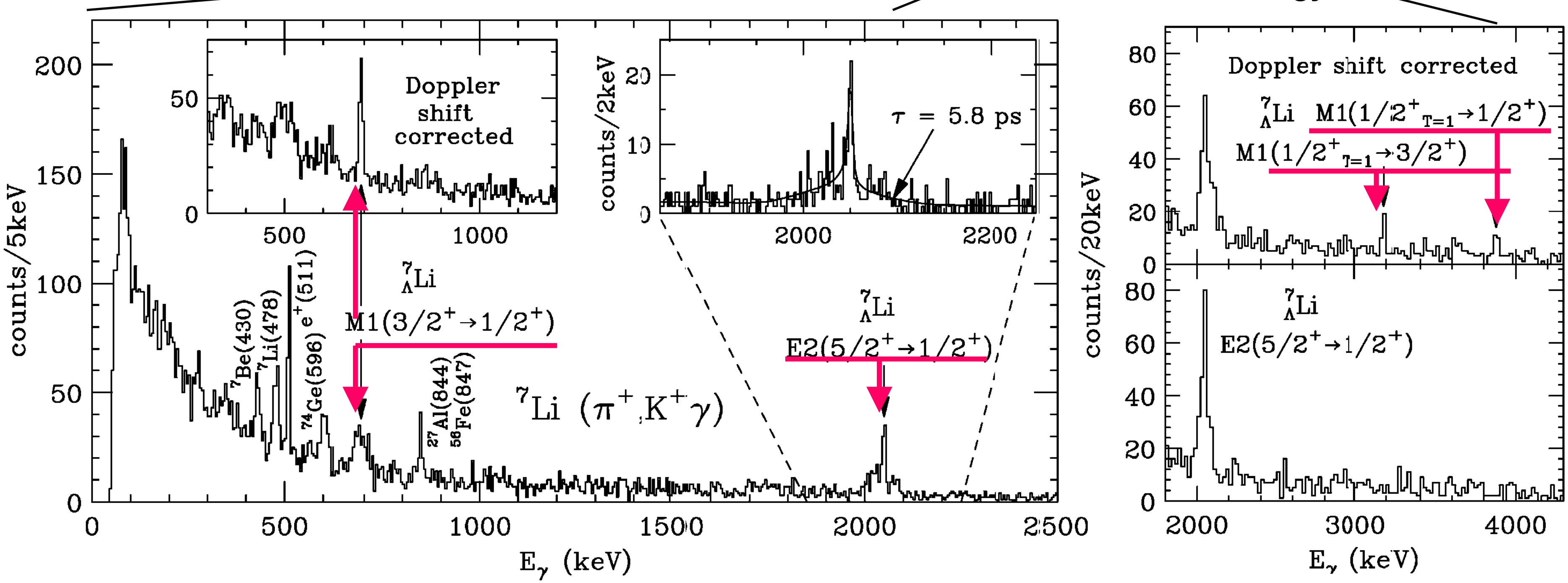




γ spectrum of $^{7}_{\Lambda}$Li

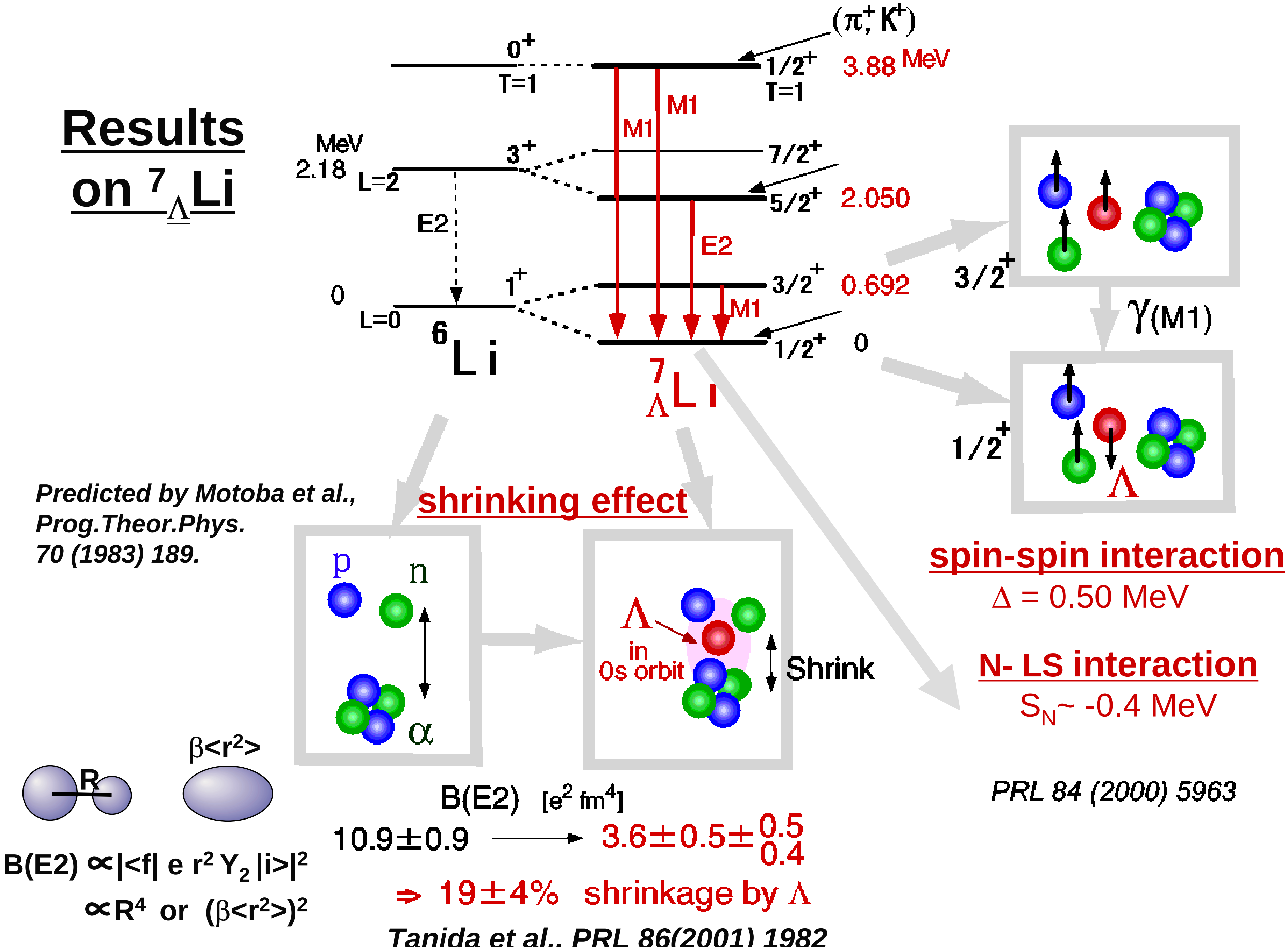
KEK E419 : SKS + Hyperball





Tamura et al., PRL 94(2000) 5963

First observation of well-identified hypernuclear γ rays with Ge.

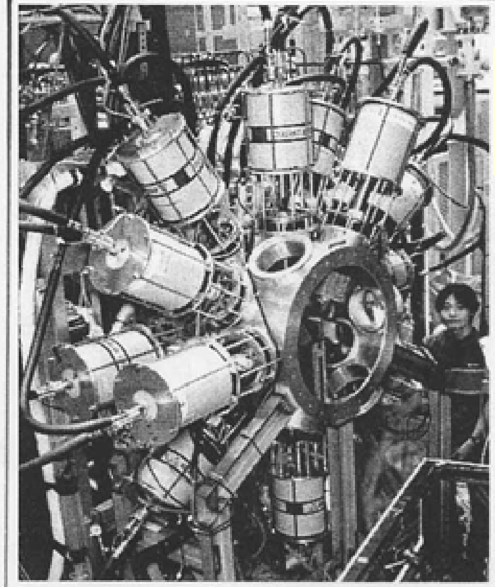


Results on 7ΛLi
(π+, K+)
0+
T=1
1/2+
T=1
3.88 MeV
M1
M1
MeV
2.18
L=2
3+
7/2+
5/2+
2.050
E2
E2
0
L=0
1+
3/2+
0.692
M1
1/2+
0
6Li
7ΛLi
3/2+
γ(M1)
1/2+
Λ
Predicted by Motoba et al., Prog.Theor.Phys. 70 (1983) 189.
shrinking effect
p
n
α
Λ
in
0s orbit
Shrink
spin-spin interaction
Δ = 0.50 MeV
N- LS interaction
SN~ -0.4 MeV
PRL 84 (2000) 5963
β<r2>
R
B(E2) [e2 fm4]
10.9±0.9
3.6±0.5±0.5/0.4
B(E2) ∝|<f| e r2 Y2 |i>|2
∝R4 or (β<r2>)2
⇒ 19±4% shrinkage by Λ
Tanida et al., PRL 86(2001) 1982

Publicity of E419 and Hyperball

PRL 84(2000) 5963
PRL 86(2001) 1982
PLB 579 (2004) 258
and more to come..

Asahi, 8 July 2000


朝日新聞　2000年(平成12年)7月8日　土曜日

科学

中性子星の世界探る一歩
ハイパー原子核を見た

ラムダ粒子という素粒子を入れた人工の原子核「ハイパー原子核」が放つガンマ線をとらえることに、田村裕和・東北大学大学院理学研究科助教授らでつくる国際共同研究チームが成功した。

私たちの身の回りは、陽子と中性子でできた原子核や、電子を中心につくられているが、星の終末の姿である中性子星にはラムダ粒子があるかもしれないといわれている。そうした一風変わった物質世界を探る一

自然界にはほとんど見られないが、中性子星には、多くの中性子、わずかな陽子、電子とともに存在するとも予想されている。

今回、チームは高エネルギー加速器研究機構（茨城県つくば市）の加速器で、陽子と中性子が三個ずつとラムダ粒子が一個入ったハ

エネルギーを調って、ラムダ粒子と陽子、中性子の間に働く力を精度よく調べた。

研究チームの永江知文・同機構素粒子原子核研究所助教授は「こうした研究が進んで中性子星中のラムダ粒子の存在が確かめられれば、中性子星の中だけとはいえ、物質は陽子と中性子と電子からなるという物質観の変更が迫られることになる」と話している。

この研究は、六月二十六日発行の米物理学誌フィジ

ハイパー原子核から出たガンマ線を測定する装置。ハイパーボールと呼ばれる＝高エネル……構提供

Butsuri, June 2001

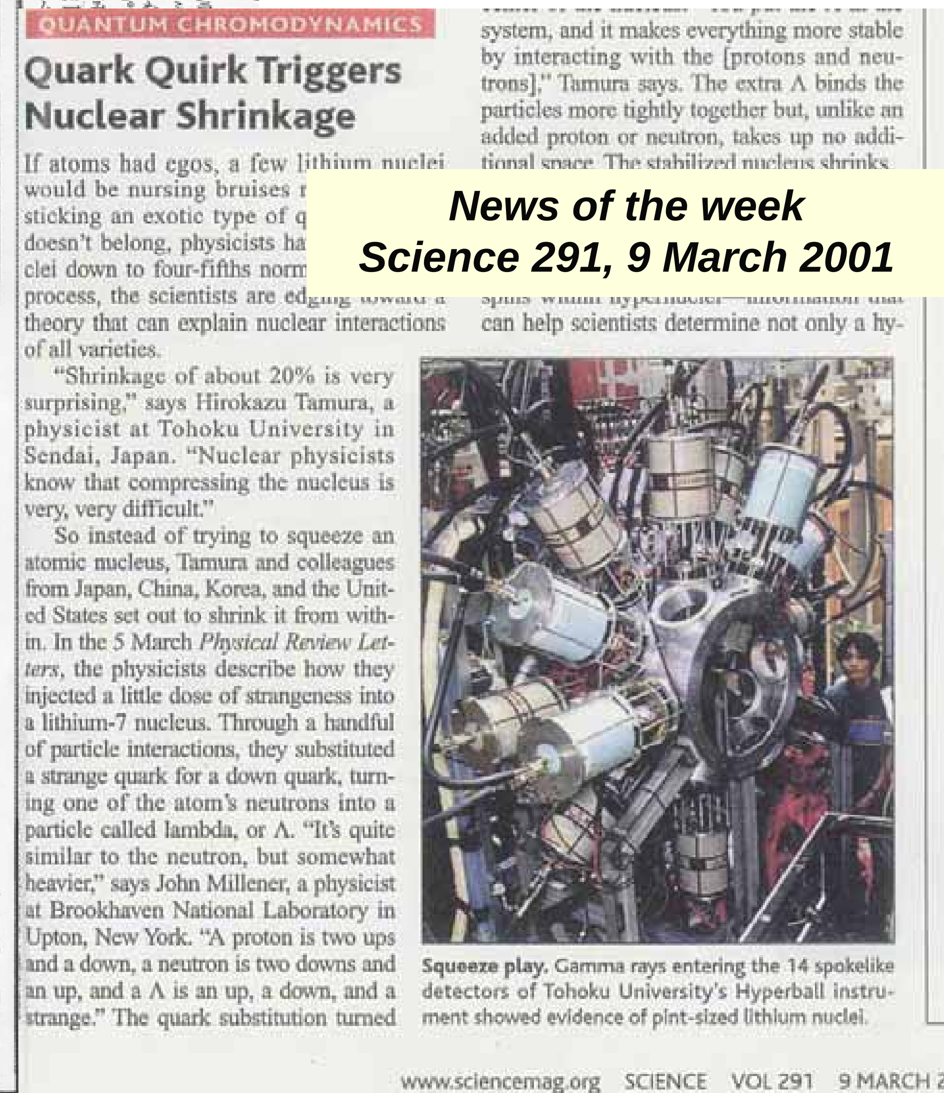

日本物理学会誌

BUTSURI

■ 日本における核融合研究開発の歴史
■ 分子計算とその物理的基礎
■ 三次元素粒子飛跡の並列画像処理

2001 VOL. 56 NO. 6

News of the week
Science 291, 9 March 2001


QUANTUM CHROMODYNAMICS

Quark Quirk Triggers Nuclear Shrinkage

If atoms had egos, a few lithium nuclei would be nursing bruises r… sticking an exotic type of q… doesn't belong, physicists ha… clei down to four-fifths norm… process, the scientists are edging toward a theory that can explain nuclear interactions of all varieties.

"Shrinkage of about 20% is very surprising," says Hirokazu Tamura, a physicist at Tohoku University in Sendai, Japan. "Nuclear physicists know that compressing the nucleus is very, very difficult."

So instead of trying to squeeze an atomic nucleus, Tamura and colleagues from Japan, China, Korea, and the United States set out to shrink it from within. In the 5 March *Physical Review Letters*, the physicists describe how they injected a little dose of strangeness into a lithium-7 nucleus. Through a handful of particle interactions, they substituted a strange quark for a down quark, turning one of the atom's neutrons into a particle called lambda, or Λ. "It's quite similar to the neutron, but somewhat heavier," says John Millener, a physicist at Brookhaven National Laboratory in Upton, New York. "A proton is two ups and a down, a neutron is two downs and an up, and a Λ is an up, a down, and a strange." The quark substitution turned

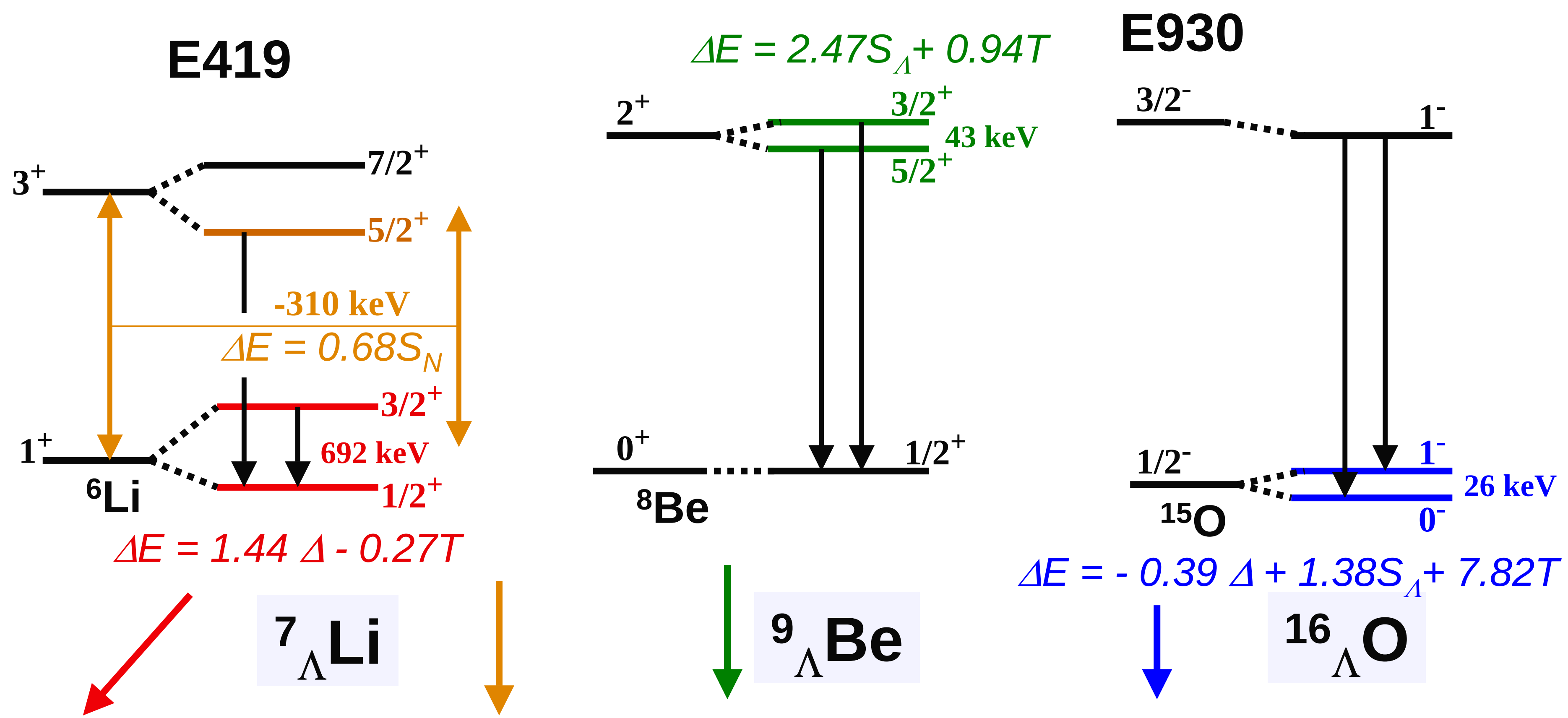
… system, and it makes everything more stable by interacting with the [protons and neutrons]," Tamura says. The extra Λ binds the particles more tightly together but, unlike an added proton or neutron, takes up no additional space. The stabilized nucleus shrinks.

… spins within hypernuclei—information that can help scientists determine not only a hy-

Squeeze play. Gamma rays entering the 14 spokelike detectors of Tohoku University's Hyperball instrument showed evidence of pint-sized lithium nuclei.

Results on ΛN interaction by E419+E930

"Hypernuclear Fine Structure"

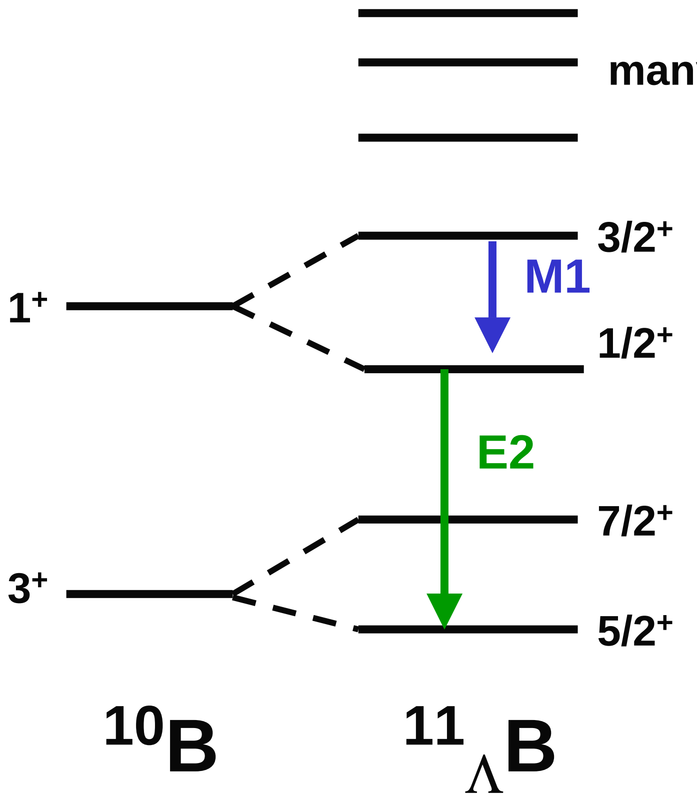


Δ = 0.4 MeV　　S_N = - 0.4 MeV　　S_Λ = - 0.01 MeV　　T = 0.03 MeV

All the spin-dependent force parameters determined.

E518: γ-Spectroscopy of $^{11}_{\Lambda}B$

Run in Oct. 2002 at K6, 80 shifts



Expected levels

Purposes:

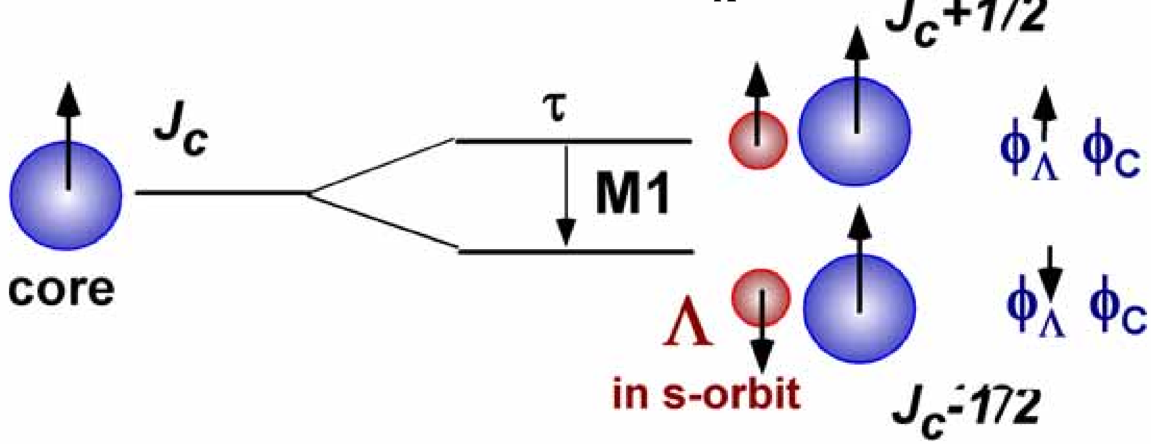
- τ(3/2+) ∼ 0.5 ps (Millener)
  Stopping time ∼ 1.0 ps by (π^+,K^+)
  -> B(M1) : measurable
  by Doppler shift attenuation method

- Level energies
  -> Cross check of
  ΛN spin-dependent interactions

B(M1) and μ_Λ in nucleus

μ_Λ in nucleus -> Possible modification of baryons in nuclear matter
Effect of meson-exchange current (small)

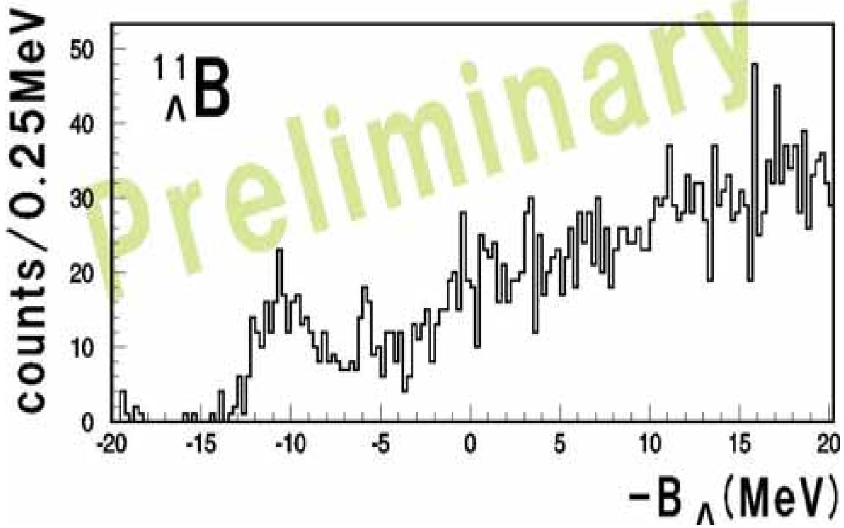
Direct measurement of μ_Λ very difficult
but
Spin-flip B(M1) -> g_Λ



$$B(M1) \propto |\langle \Phi_f \,|\, \mu^z \,|\, \Phi_i \rangle|^2$$
$$= |\langle \phi_\Lambda^\downarrow\ \phi_C |\ g_c J_c^z + g_\Lambda J_\Lambda^z \ | \phi_\Lambda^\uparrow\ \phi_C \rangle|^2$$
$$\propto (g_c - g_\Lambda)^2$$

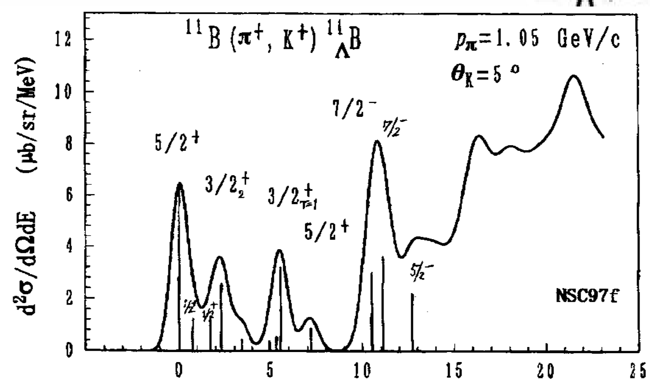
Dalitz and Gal, Ann.Phys.116(1978)167.

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

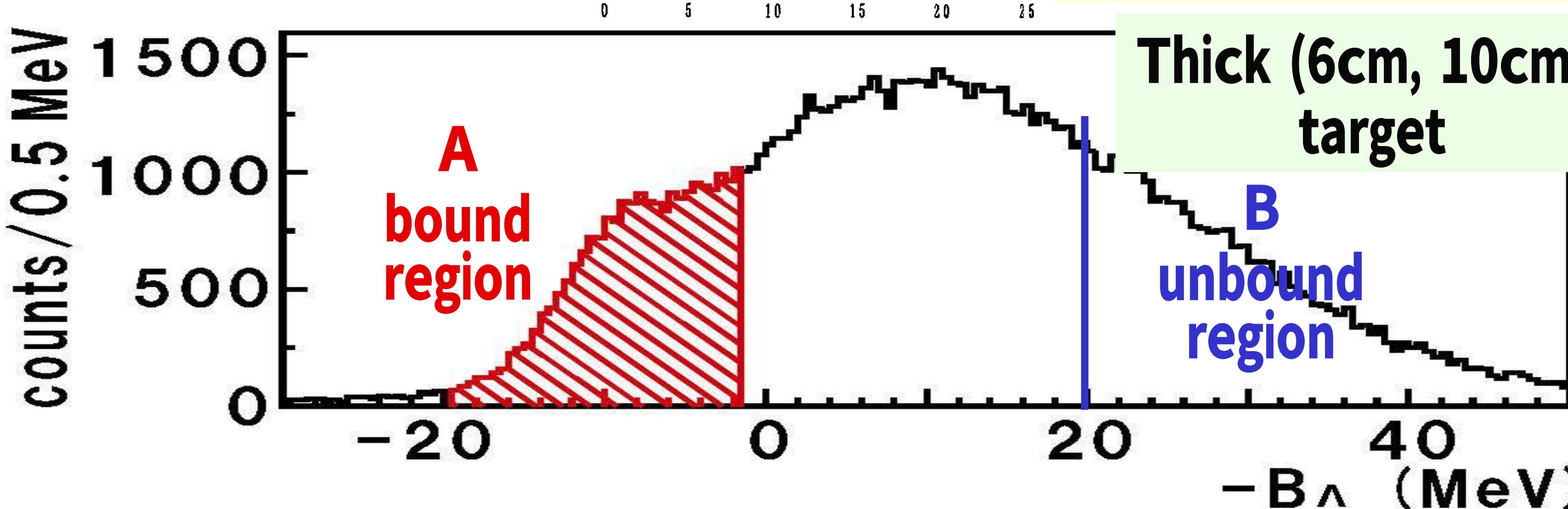


Thin (1cm) target

Calc. by Motoba

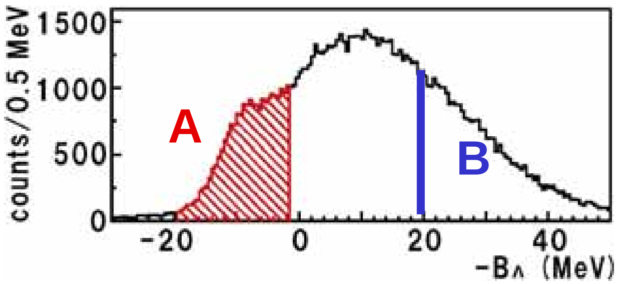


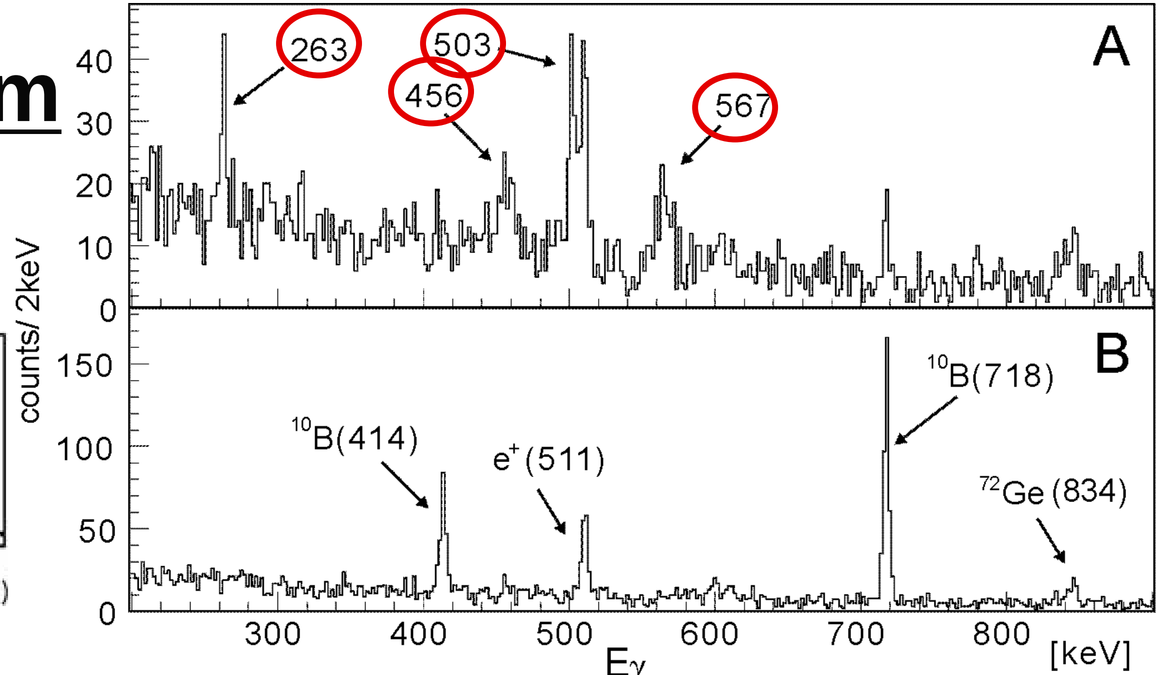
10cm target : 0.85×10^{12} π^+
6cm target : 0.75×10^{12} π^+
(Proposal : 10cm, 2.1x10^{12} π^+)
=>
Beam x Target thick. x Ge eff.
= 50% of proposal



Thick (6cm, 10cm) target

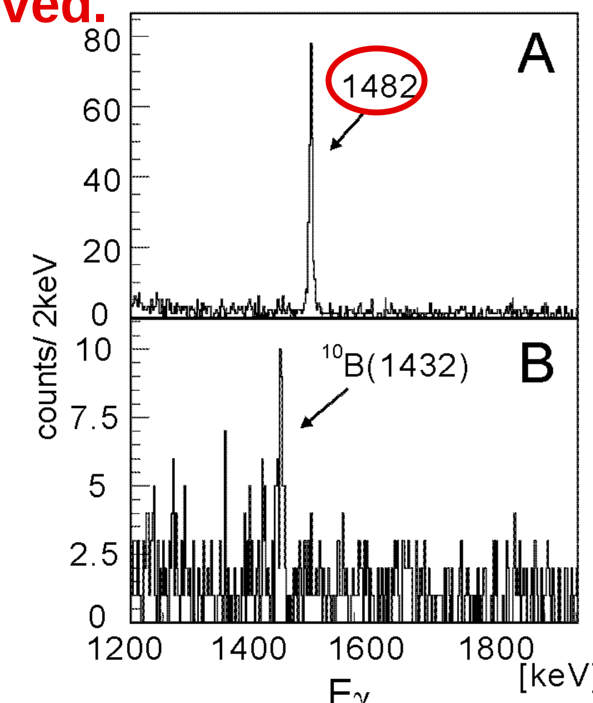
γ-Ray Spectrum of $^{11}_{\Lambda}B$

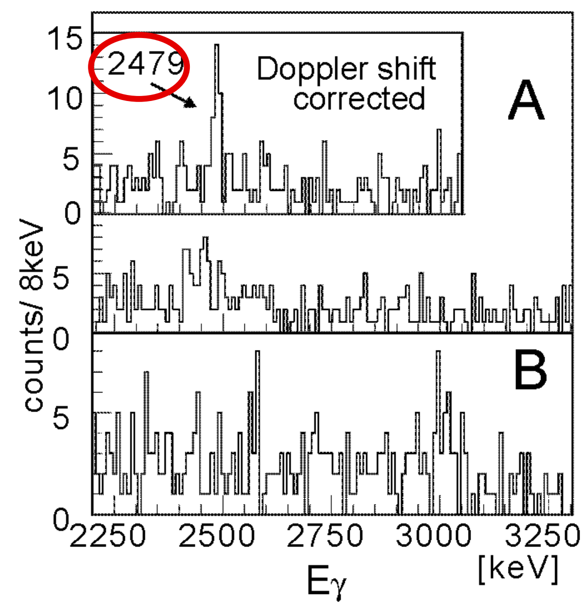




Six $^{11}_{\Lambda}B$ γ-rays observed.

Eγ (keV)	Number of Events	Relative Intensity
262	71	0.14
454	54	0.13
500	50	0.13
564	78	0.21
1482	203	1.00
2479	45	0.37
3286	10	0.10



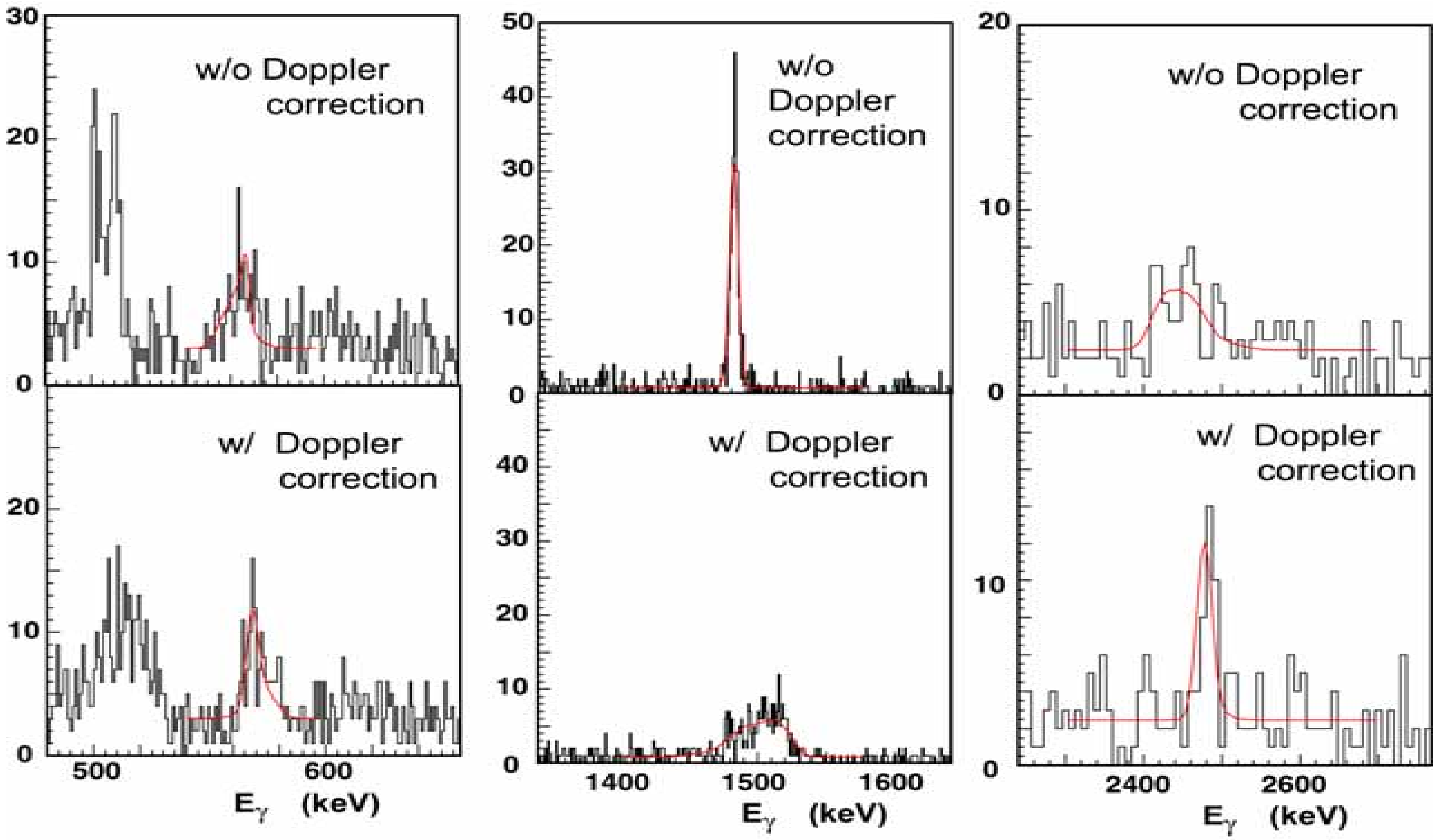


Lifetime Fit

Preliminary
stat.error only

E_γ (keV)	lifetime (ps)
263.4±0.05	0.39+0.16-0.11
456.6±0.02	0.21+0.08-0.05
503.7±0.02	0.34+0.09-0.06
567.0±0.02	0.15+0.03-0.02
1481.9±0.02	> 5.24
2474.7±0.02	0.04+0.03-0.02

Fit both spectra (w/o and w/ Doppler correction)
with simulated peak shapes for various lifetimes



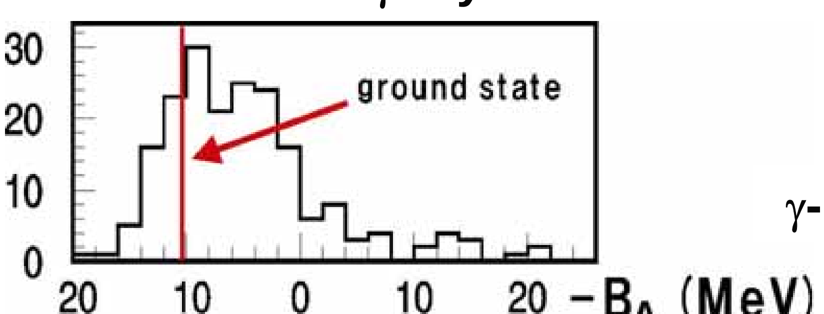
=> 0.15+0.03-0.02 ps   => > 5.24 ps   => 0.04 +0.03-0.02 ps

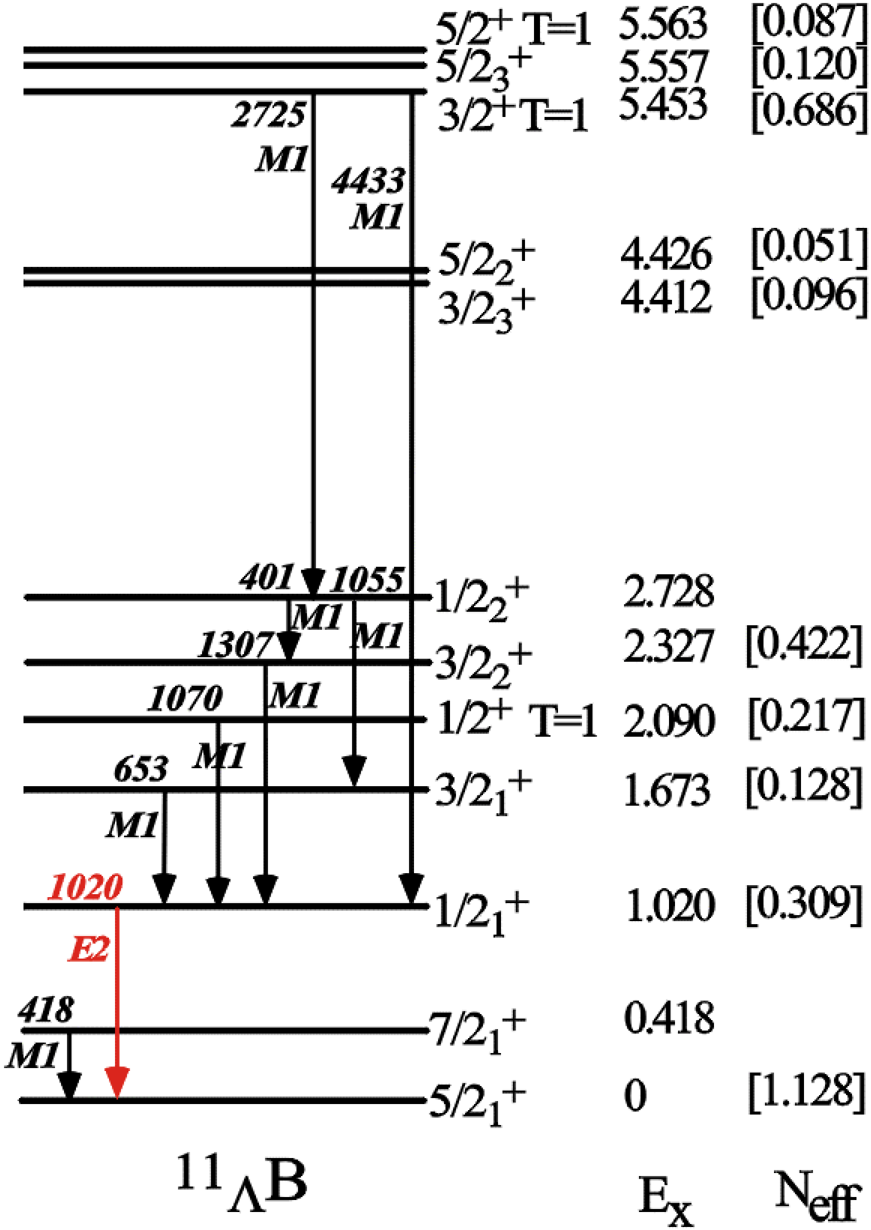
Assignment of $^{11}{}_{\Lambda}$B (1482 keV) line

E2 ($1/2^+_1 \rightarrow 5/2^+_1$) because

- Long lifetime-- too long for M1
  (>5 ps => $B(M1) < 10^{-3}$ [μ_N^2])
- Largest yield -- $1/2^+_1$ collects yields from upper levels
- Gated mass spectrum – showing contribution from upper levels also

$^{11}{}_{\Lambda}$B mass spectrum for 1482 keV γ-ray events





γ-rays expected to be observed (Millener)

E518 Present Status

- Six transitions in ${}^{11}_{\Lambda}$B were observed.

- E2 energy (1482 keV) significantly larger than the prediction (1020 keV) from already-determined parameters

$$\Delta E(1/2_1^+ \rightarrow 5/2_1^+) = \Delta E_{core} - 0.243\Delta + 1.234 S_\Lambda - 1.090 S_N - 1.627 T + \Lambda\Sigma$$

-> S_N inconsistent with the other data (${}^{7}_{\Lambda}$Li, ${}^{12}_{\Lambda}$C, ${}^{13}_{\Lambda}$C, ${}^{16}_{\Lambda}$O)
-> core (^{10}B) w.f. incorrect? –- feedback to structure of normal nuclei?

PLB to be published.

- Assignment of all the other observed γ-rays seems difficult
  -- γγ coincidence necessary with a higher efficiency detector

E509: Hypernuclear Spectroscopy of hyperfragments with stopped K$^-$

April 2002, 40 shifts, K.Tanida

Direct reactions : (π^+, K$^+$ γ), (K$^-$, π^- γ)

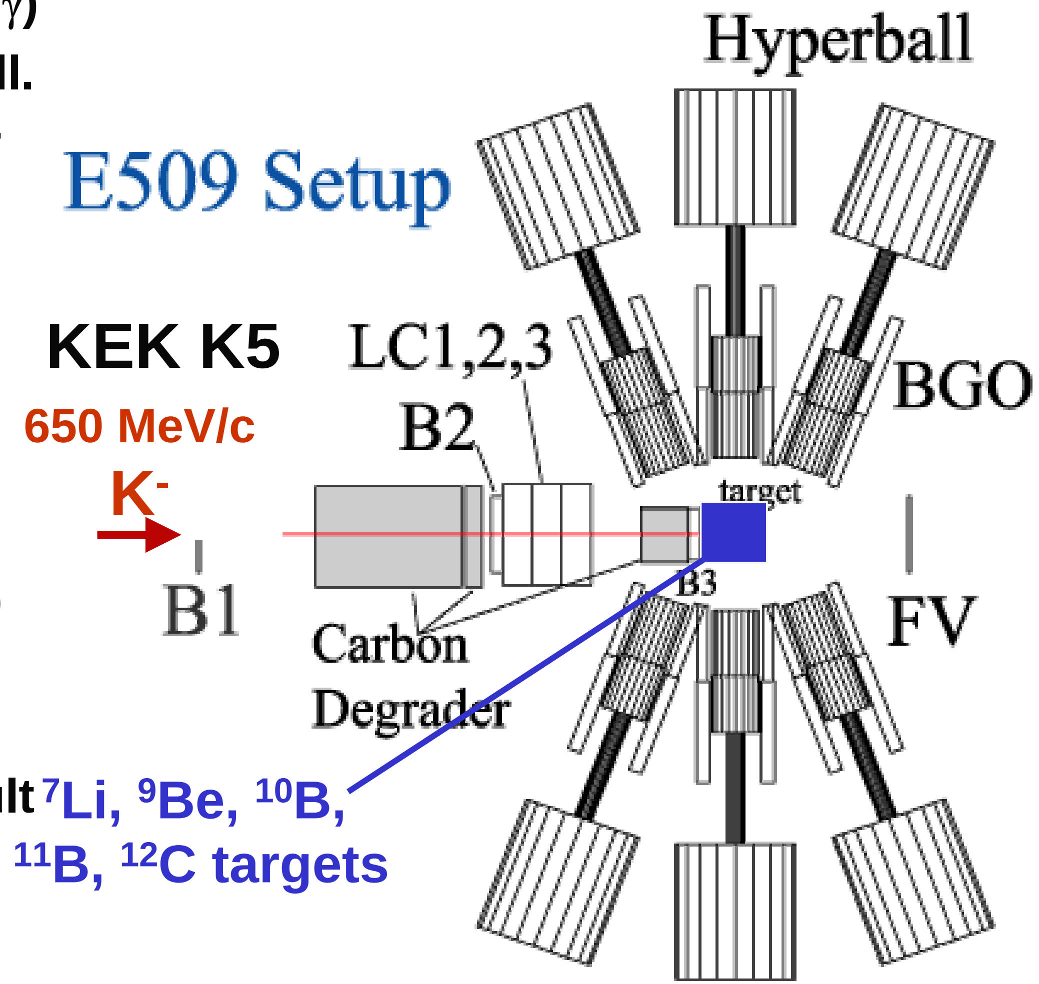
- **Hypernuclei can be idenitified well.**
- **But, low yields – ~one month per target**

Indirect reaction: (stopped K$^-$, γ)

-- in-beam method

- **Large production yield of "hyperfragments" from stopped K$^-$ absorption (~10% per stopped K$^-$)**
- **Various hypernuclear species including n/p-rich ones**
- **But, more background and difficult identification**

--> Test feasibility



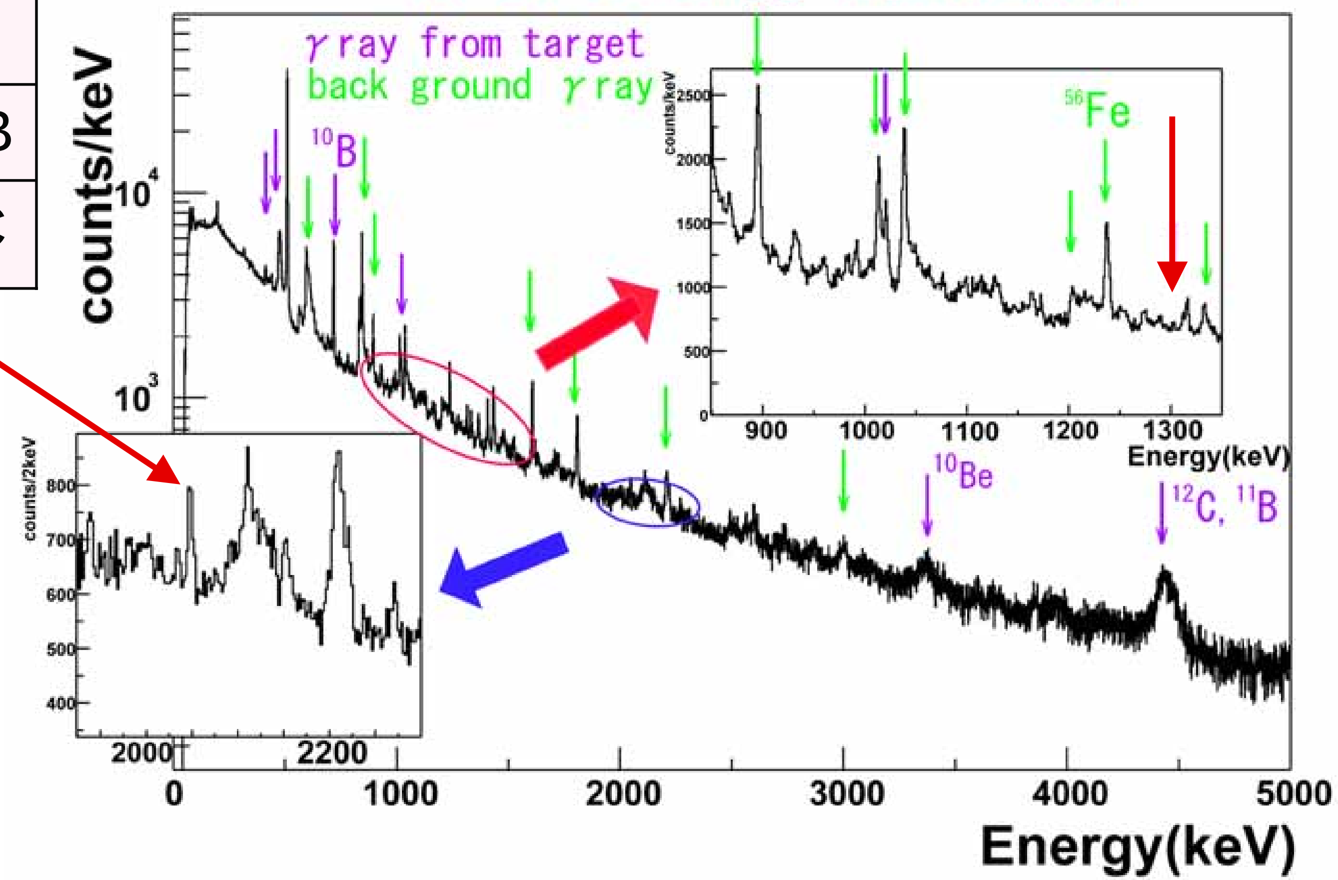
(stopped K^-, γ) spectrum

Candidates of hypernuclear γ rays

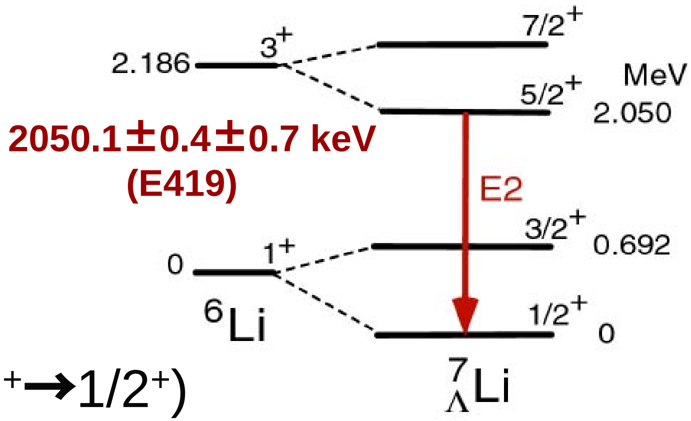
- **Not normal nuclear γ rays**
- **Target dependence**
- **Prompt timing (< 5ns)**

E_γ (keV)	target
1302	$^{9}Be, ^{10}B, ^{11}B$
2049	$^{10}B, ^{11}B, ^{12}C$

^{10}B target



E509 results (1): 2049 keV line

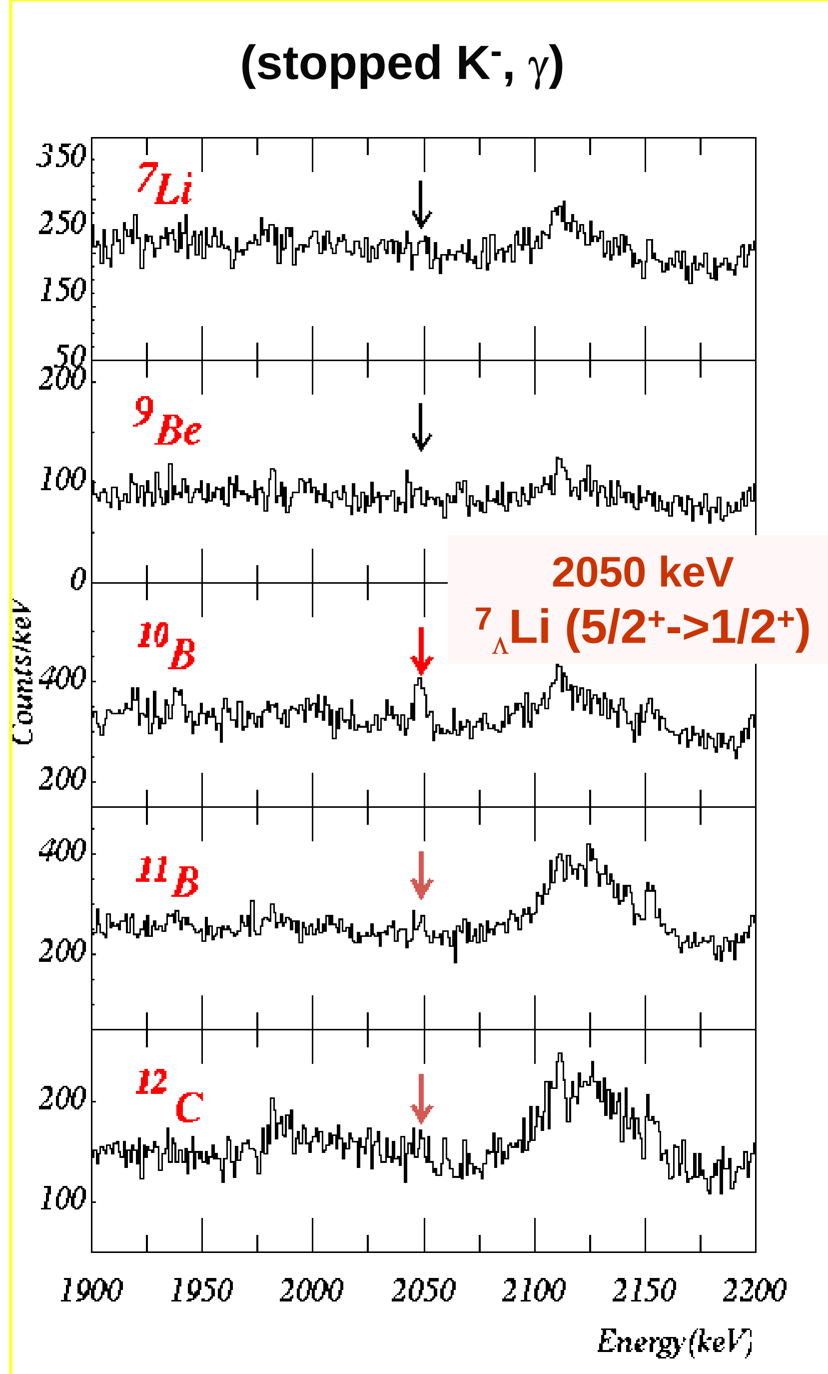


- $^{7}_{\Lambda}$Li : E2($5/2^+ \rightarrow 1/2^+$) observed with a large yield,
  516±74 counts in 3.5 days

  c.f. E419 ^{7}Li (π^+,$K^+\gamma$) $^{7}_{\Lambda}$Li
  188±17 counts in 25 days

  => Abundant γ-ray yield

- Production rate of $^{7}_{\Lambda}$Li ($5/2^+$) :
  0.075±0.016% per stopped K^- on ^{10}B
  PLB to be published.
- $^{7}_{\Lambda}$Li : M1($7/2^+ \rightarrow 5/2^+$) not observed
  (small statistics for $\gamma\gamma$ coincidence)



E509 results (2): 1303 keV line

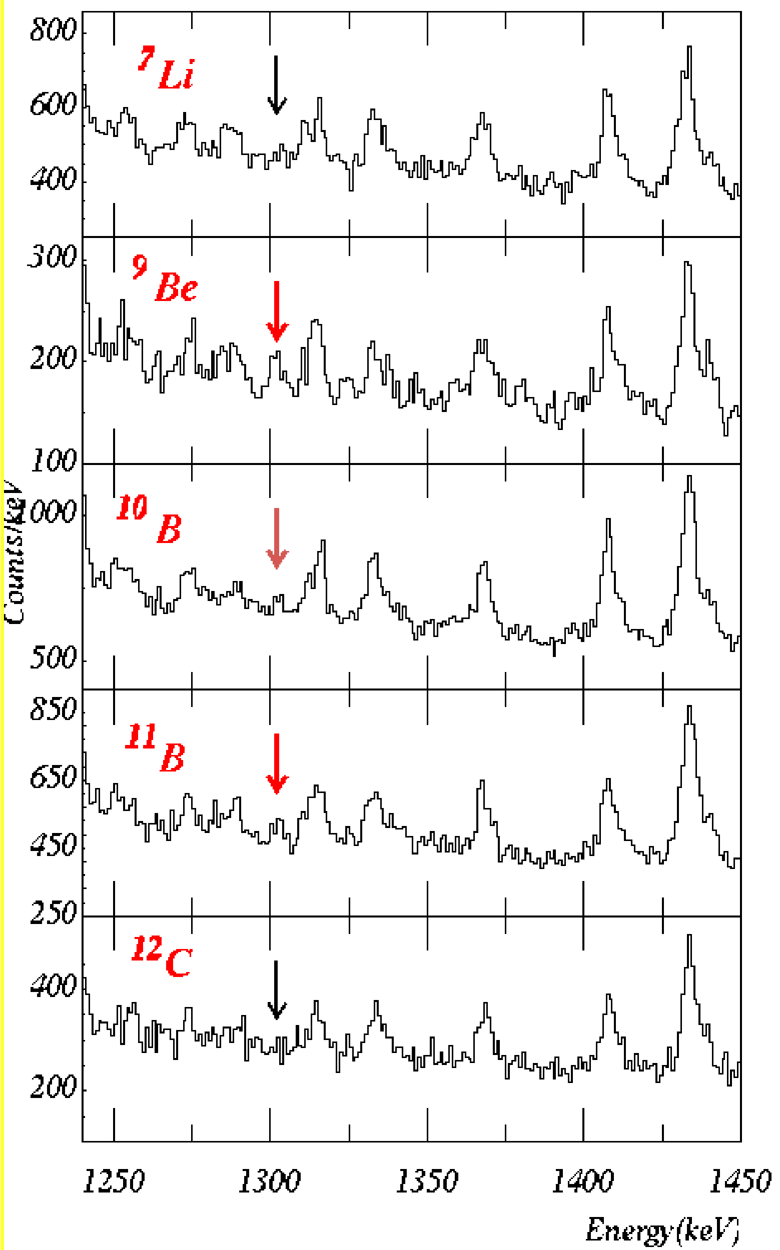
Unknown candidate of hypernuclear γ ray at 1302.0±0.6 keV

-> $^{8}_{\Lambda}$Li, $^{9}_{\Lambda}$Li, .. ?

E509 summary

(stopped K^-,γ) is found useful, but

- **$\gamma\gamma$ coincidence necessary**
- **combination with direct reactions**



Future Plans

Before J-PARC

- Construction of Hyperball2 – finishing soon.
- KEK: $^{12}_{\Lambda}C$ /$^{11}_{\Lambda}B$, $^{4}_{\Lambda}He$ at K6 (2005), to be proposed.

-- ΛN force cross-check by $^{12}_{\Lambda}C$: solve inconsistency problem of $^{10}_{\Lambda}B$
necessary for J-PARC strategy

-- B(M1) of $^{11}_{\Lambda}B$ possible

-- $^{4}_{\Lambda}He$ for Charge Symmetry Breaking

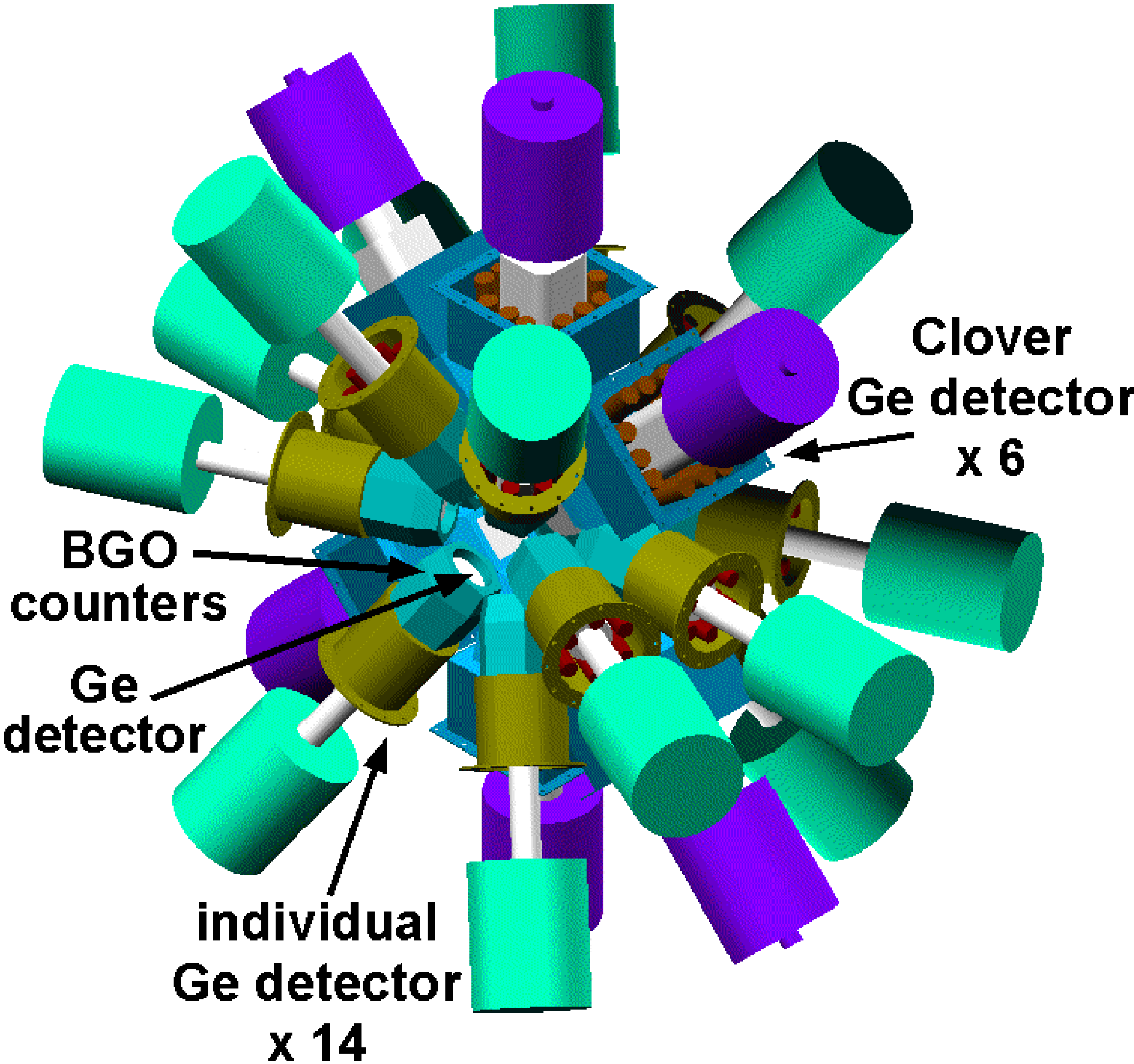
- BNL: E930-3 (more p-shell), E964 Ξ-atomic X-rays
--approved but difficult to get beam time.
- Preparation for J-PARC (R&D for a “faster” system)
- Training of students at Jlab (Hall-C) and DAFNE(FINIDA)

J-PARC: γ spectroscopy is a “Day-1” experiment.

- Systematic study of all light (A<30) hypernuclei
- Medium heavy hypernuclei
- Mirror and n-rich hypernuclei using (K^-,π^0) and hyperfragments (CSB, shrinkange of n-halo,..)
- Systematic measurement of B(M1) for magnetic moment of Λ in a nucleus

Hyperball2 under construction, ready by fall, 2004

- Clover Ge (r.e. >120%)
  +BGO x 6 added
- Photo-peak efficiency
  ~ 2.5% -> 5% at 1 MeV
  γγ efficiency -> x 4
- VME-based fast readout
- Test Exp at Tohoku Cyclotron
- To be used at KEK and BNL in 2005-



Summary and Remarks

Precision γ spectroscopy of Hypernuclei achieved

10^3 improvement of resolution

-> ΛN interaction, shrinking effect, g_Λ in nucleus

A breakthrough in strangeness nuclear physics

Why was it born at KEK-PS so successfully?

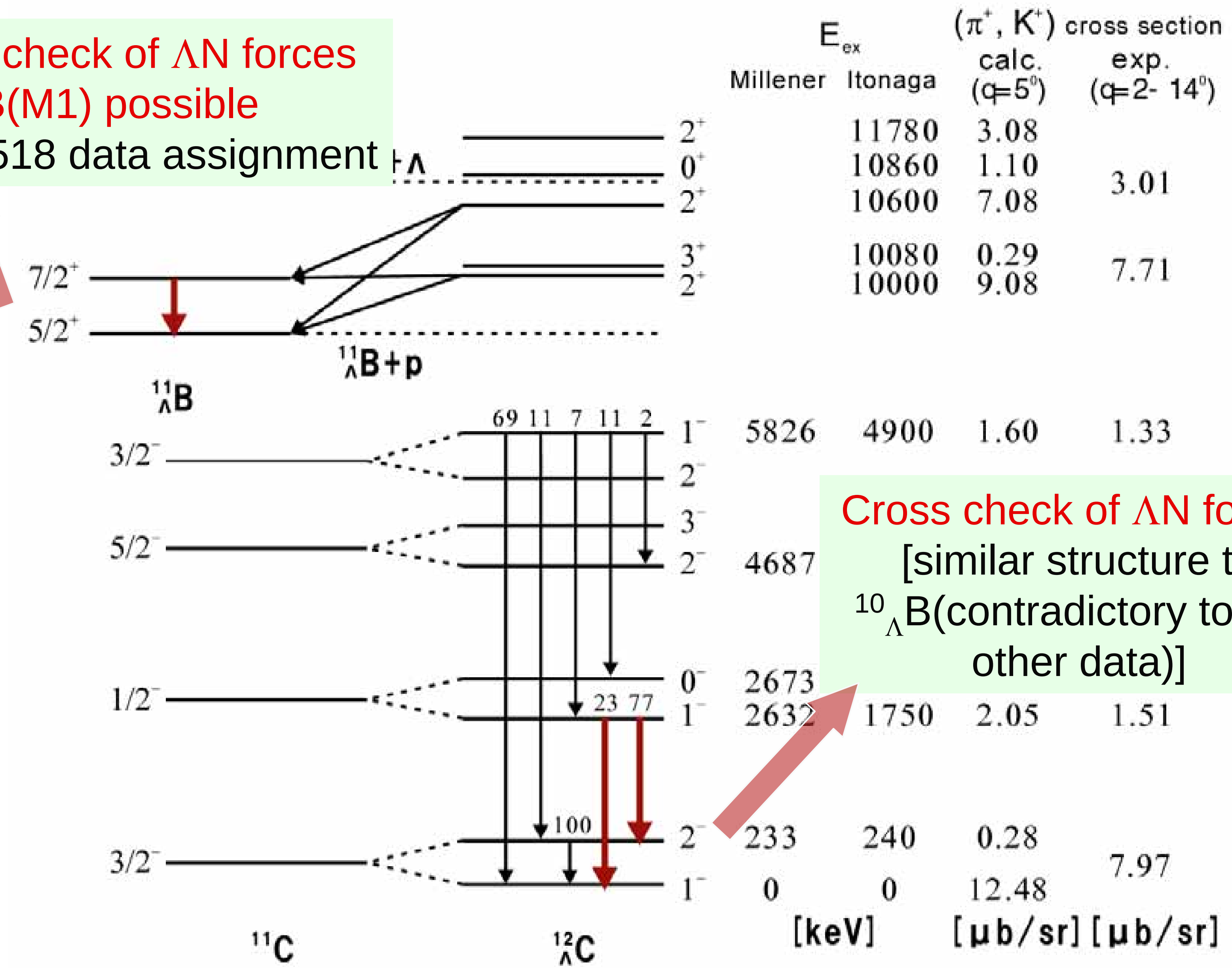
- **Well established SKS system and Perfect support by SKS group**
- **Frequent beam time ('95-'98) for Hyperball R&D and training students**

-> Please minimize no-beam period before J-PARC.

-> Construction of "Standard System" =SKS at J-PARC is indispensable.

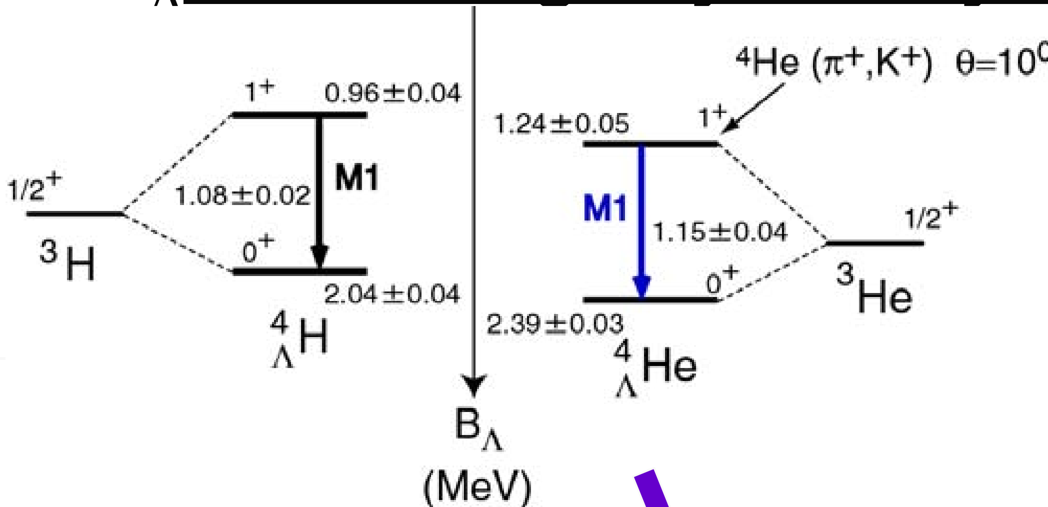
$^{12}_{\Lambda}C$ / $^{11}_{\Lambda}B$ and $^{4}_{\Lambda}He$ with K6/SKS

Cross check of ΛN forces
B(M1) possible
Help E518 data assignment



Cross check of ΛN forces
[similar structure to $^{10}_{\Lambda}B$(contradictory to the other data)]

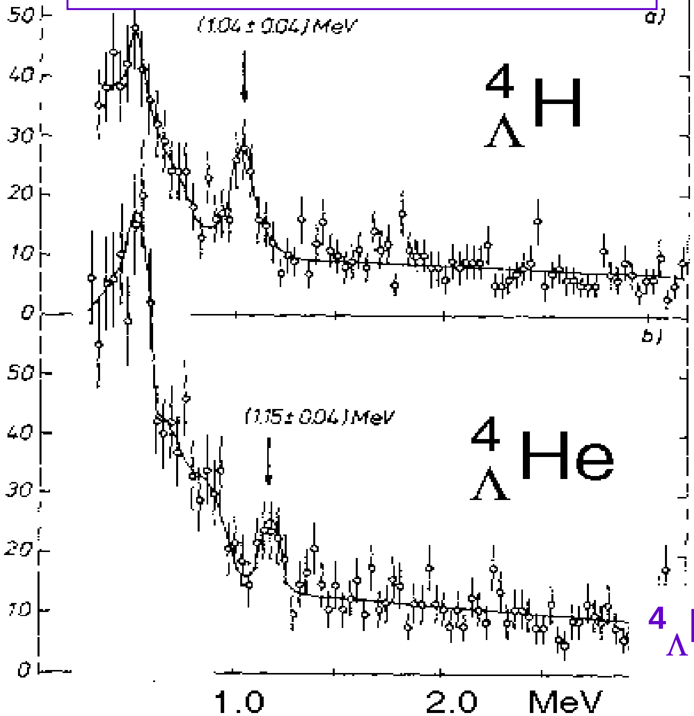
$^{4}{}_{\Lambda}$He – Charge Symmetry Breaking



Observed CSB looks spin-independent.

ΛN-ΣN coupling gives spin-dependent CSB.

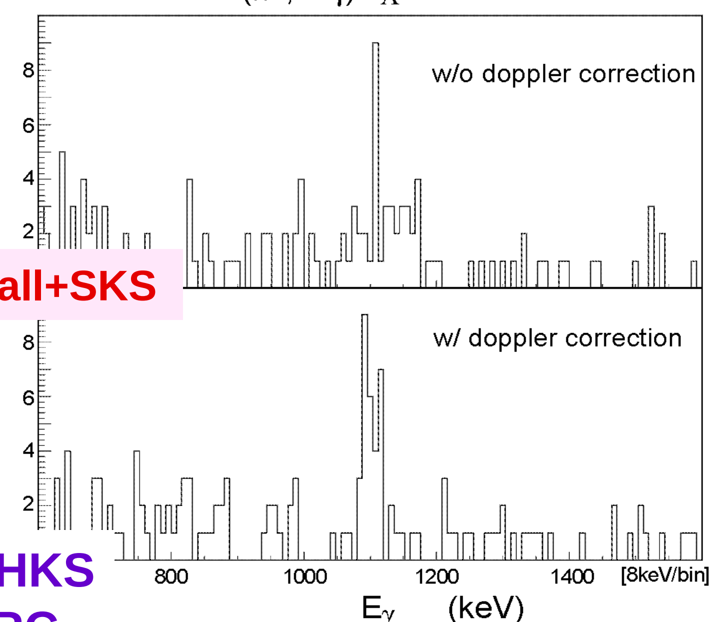
stop K$^-$ on ^{6}Li by NaI (1979)



Only one data
Bad quality

Liq. ^{4}He 10cm (1.25 g/cm^2)
0.4x10^{12} π^+ (20 shifts)
SKS 0 deg

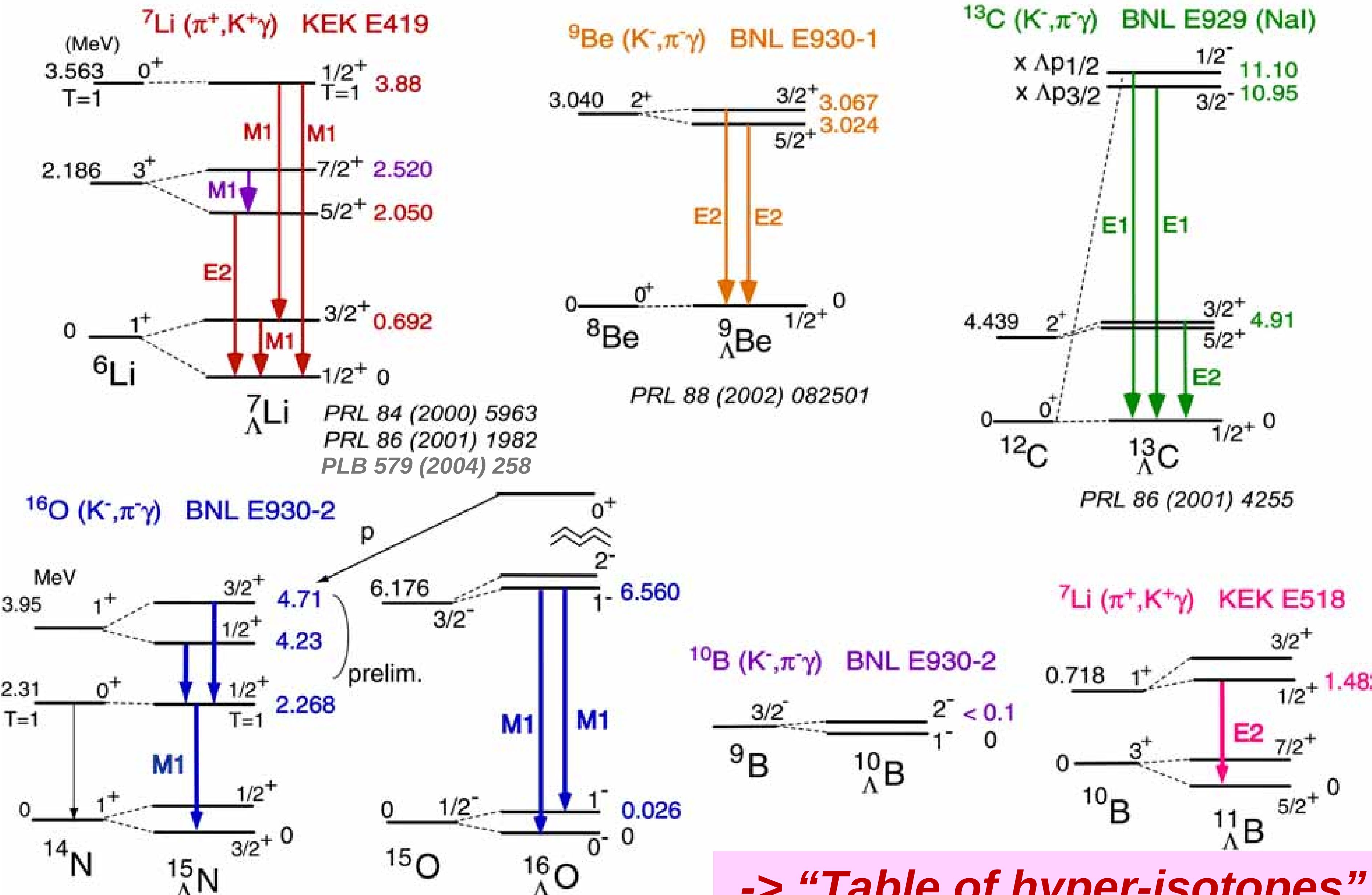
^{4}He (π^+,K$^+\gamma$) $^{4}{}_{\Lambda}$He simulation



Hyperball+SKS

$^{4}{}_{\Lambda}$H* : (e,e'K$^+$) at Jlab/HKS
(K$^-$,$\pi^0\gamma$) at J-PARC

Present status of γ spectroscopy



-> "Table of hyper-isotopes"

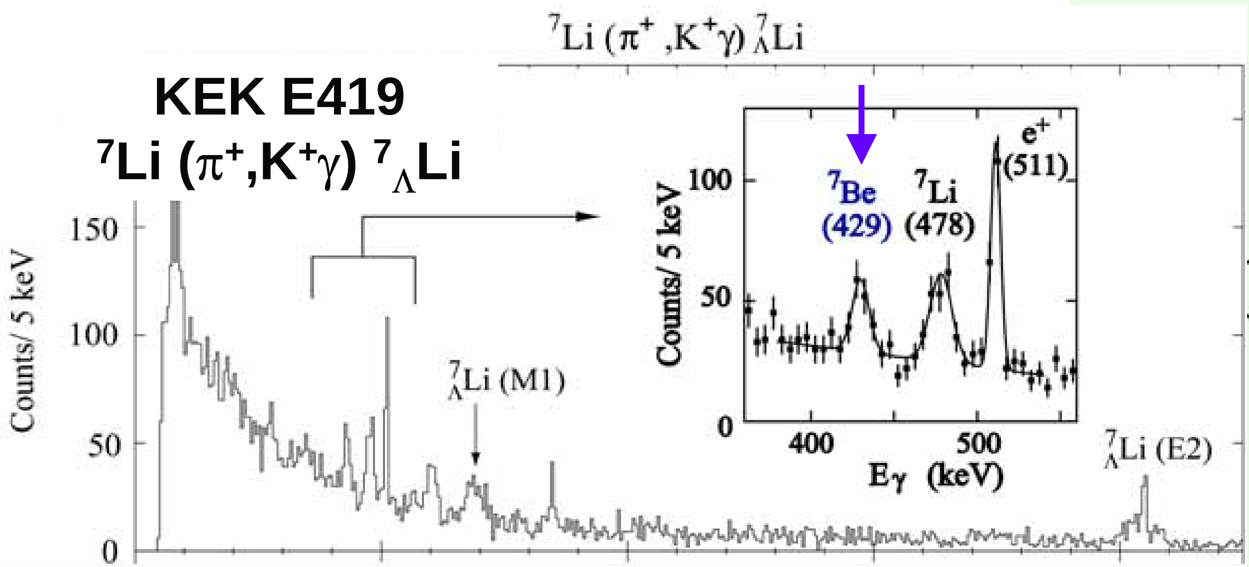
$^{7}_{\Lambda}$Li
Best-studied Hypernucleus

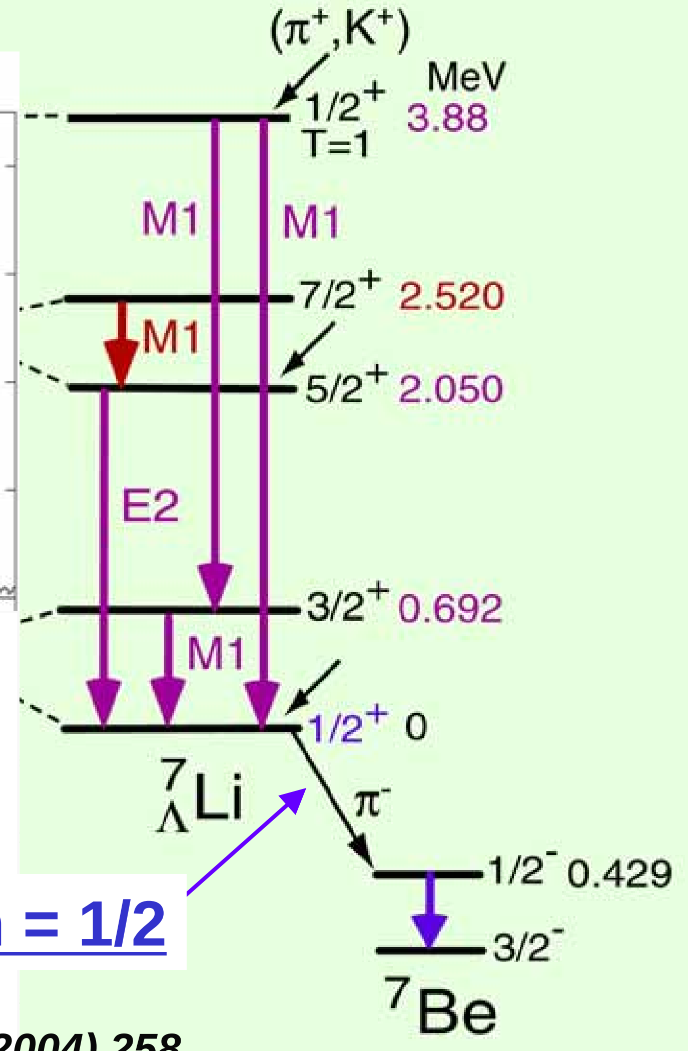
E419: ^{7}Li (π^{+},K^{+}) $^{7}_{\Lambda}$Li

E930-2: ^{10}B (K^{-},π^{-}) $^{10}_{\Lambda}$B* -> $^{7}_{\Lambda}$Li*

KEK E419

^{7}Li $(\pi^{+},K^{+}\gamma)$ $^{7}_{\Lambda}$Li





Non-spin-flip in weak decay Λ ->N π

$^{7}_{\Lambda}$Li $(1/2^{+})$ -> $^{7}_{\Lambda}$Be*$(1/2^{-})$ + π^{-}
$^{7}_{\Lambda}$Li $(3/2^{+})$ -> $^{7}_{\Lambda}$Be*$(3/2^{-})$ + π^{-}

g.s.spin = 1/2

Sasao et al., PLB 579 (2004) 258

Plans of γ spectroscopy at J-PARC (+ Hyperball-J)

(1) Complete study of light (A<30) hypernuclei

(2) Systematic study of medium and heavy hypernuclei

$(K^-, \pi^- \gamma)$ *spin-flip/ no-flip productions*

ΛN force (ΛN–ΣN, p-wave,..)

B(E2)-> shrinkage, New symmetries

(3) n-rich/ p-rich/ mirror hypernuclei

$(K^-, \gamma\gamma)$ *in-beam method*

$(K^-, \pi^0 \gamma)$ *mirror hypernuclei*

Charge sym. break in ΛN force

Shrinkage of n-halo

(4) Spin-flip *B(M1)*

$(K^-, \pi^- \gamma)$, $(\pi^+, K^+ \gamma)$ *Doppler shift atten.*

$(K^-, \pi^- \gamma\ p)$ *γ-weak coincidence*

μ_Λ in nuclei (ρ-dependence)

(5) Double strangenss (Ξ^- atom X rays and $\Lambda\Lambda$-hypernuclei)

$(K^-, K^+ \gamma)$

ΞN, $\Lambda\Lambda$ interactions