AGATA workshop
March 23, 2004

Structure of Λ Hypernuclei Studied by γ-Ray Spectroscopy

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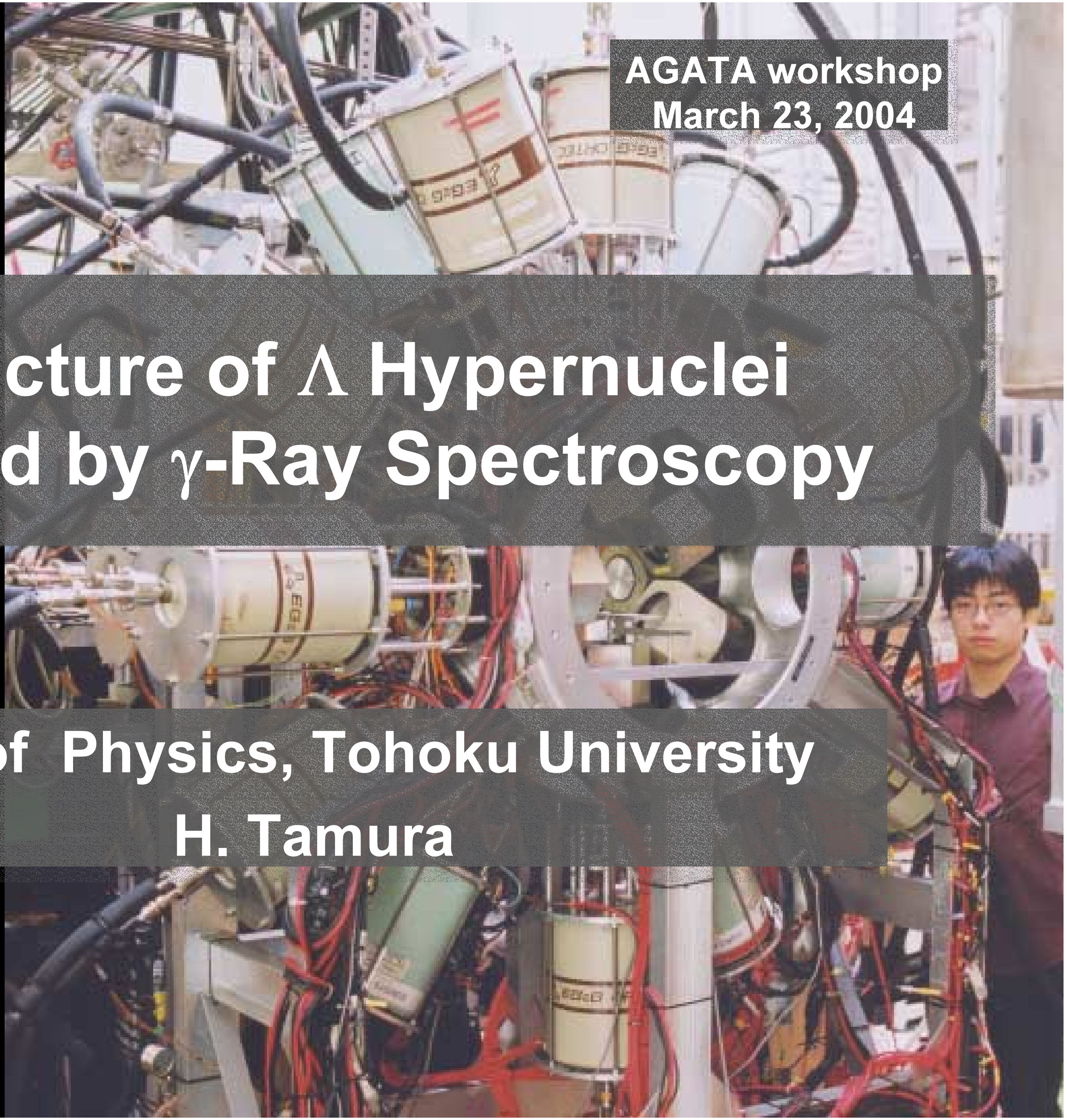

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   Motivations and “Hyperball”

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   “Hypernuclear fine structure” and ΛN force

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   “J-PARC” and “Hyperball-J” / “AGATA”

4. Summary

Hyperball collaboration (1998, 2001,2002)
E930, E509, E518

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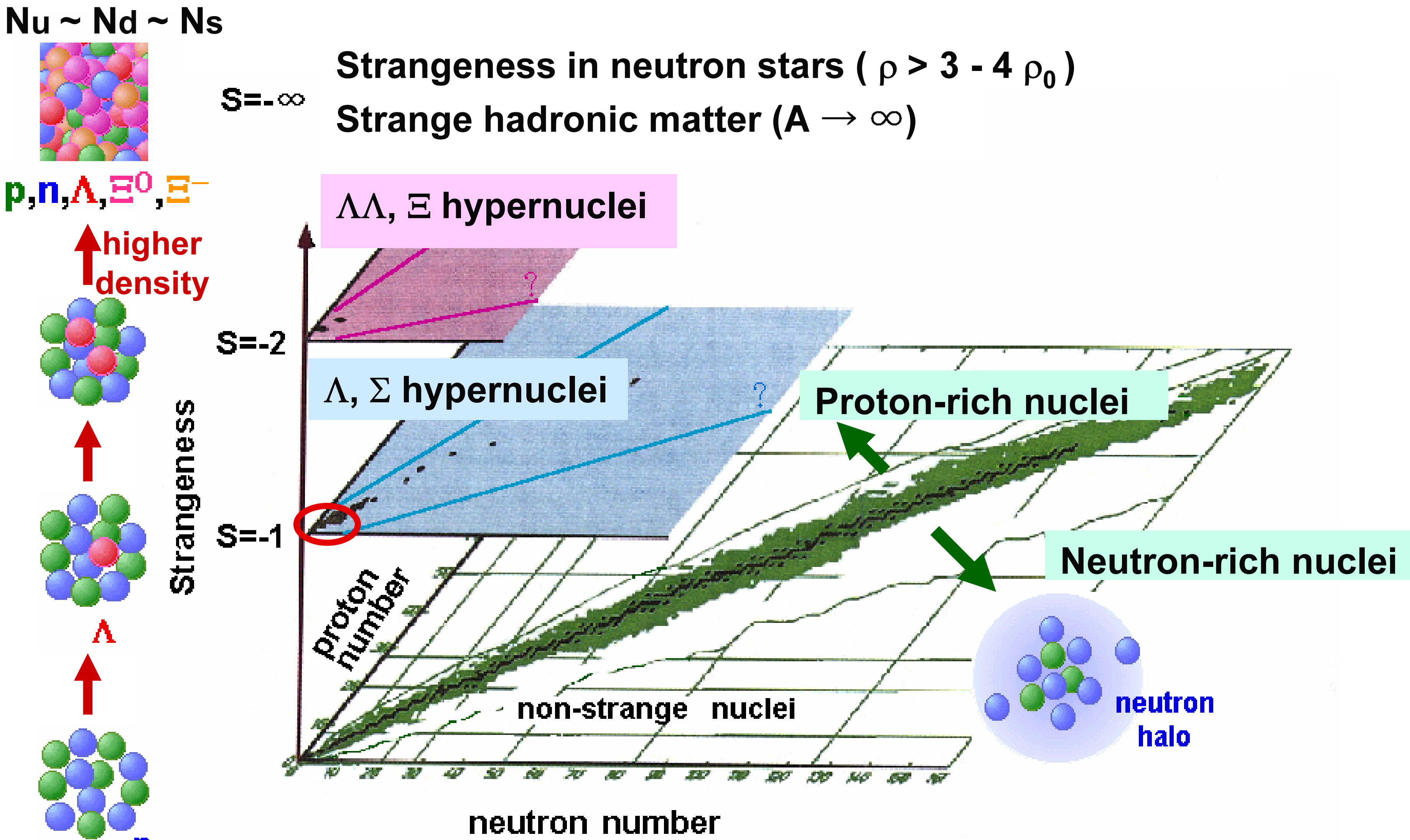
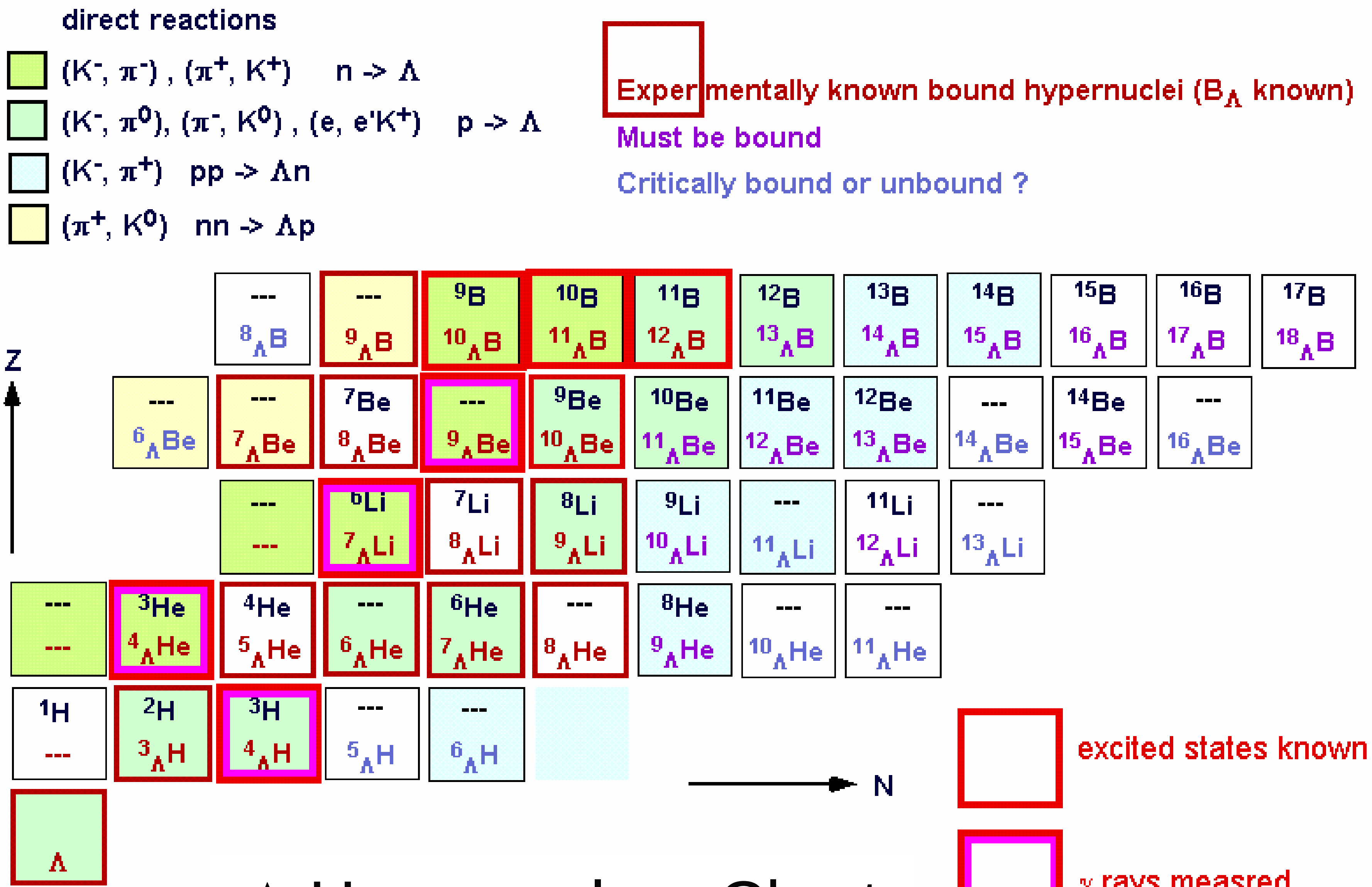
Why Hypernuclei?
-- Extending Our Knowledge on Matter



3-dimensional nuclear chart



Λ Hypernuclear Chart

Motivations of hypernuclear γ spectroscopy

- **Baryon-baryon interactions**

  Λ hypernuclear structure $\leftrightarrows$ *ΛN int. (meson or quark models)*

  c.f. *nuclear structure* $\longleftarrow$ *NN int. (phenomenologically known)*

  Unified understanding of B-B interactions

- **Impurity effects**

  Change of size and shape (shrinkage),

  New symmetries, Change of collective motions,...

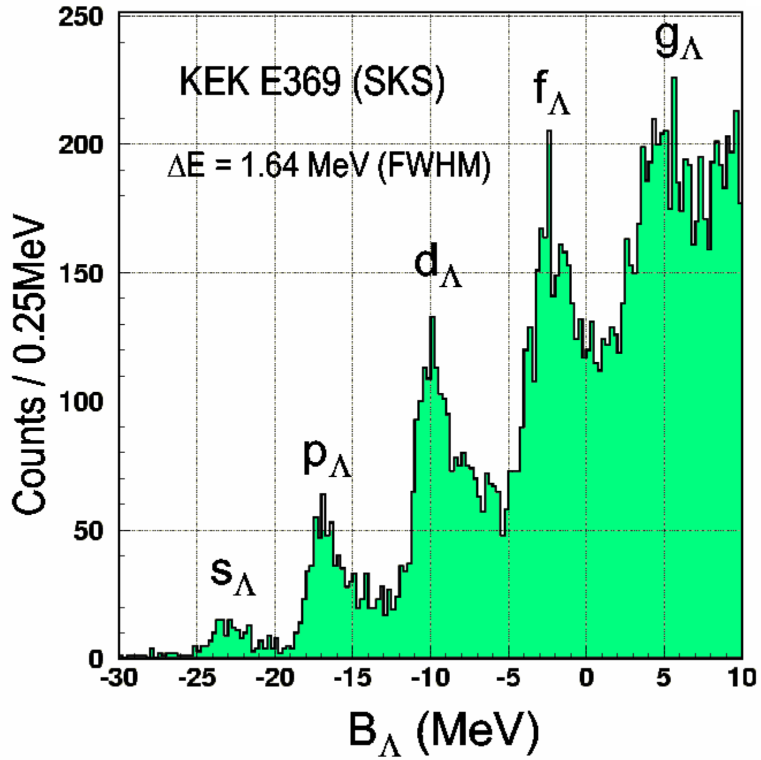
- **Medium effects** probed by hyperons free from Pauli

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

YN forces from hypernuclear structure

Hotchi et al., PRC 64 (2001) 044302

$^{89}Y\ (\pi^+,K^+)\ ^{89}_{\Lambda}Y$

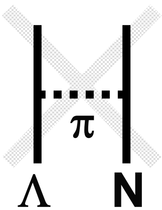


Λ Single particle states

-> potential depth

U_Λ = -30 MeV

$V_{\Lambda N} < V_{NN}$



forbidden

ΛN spin-spin, spin-orbit, tensor forces ?

ΛN <-> ΣN coupling force?

=> precise data necessary

NN interaction

$SU_f(3)$ + meson/ quark models

Free YN interaction

G-matrix calc.

Effective YN int.

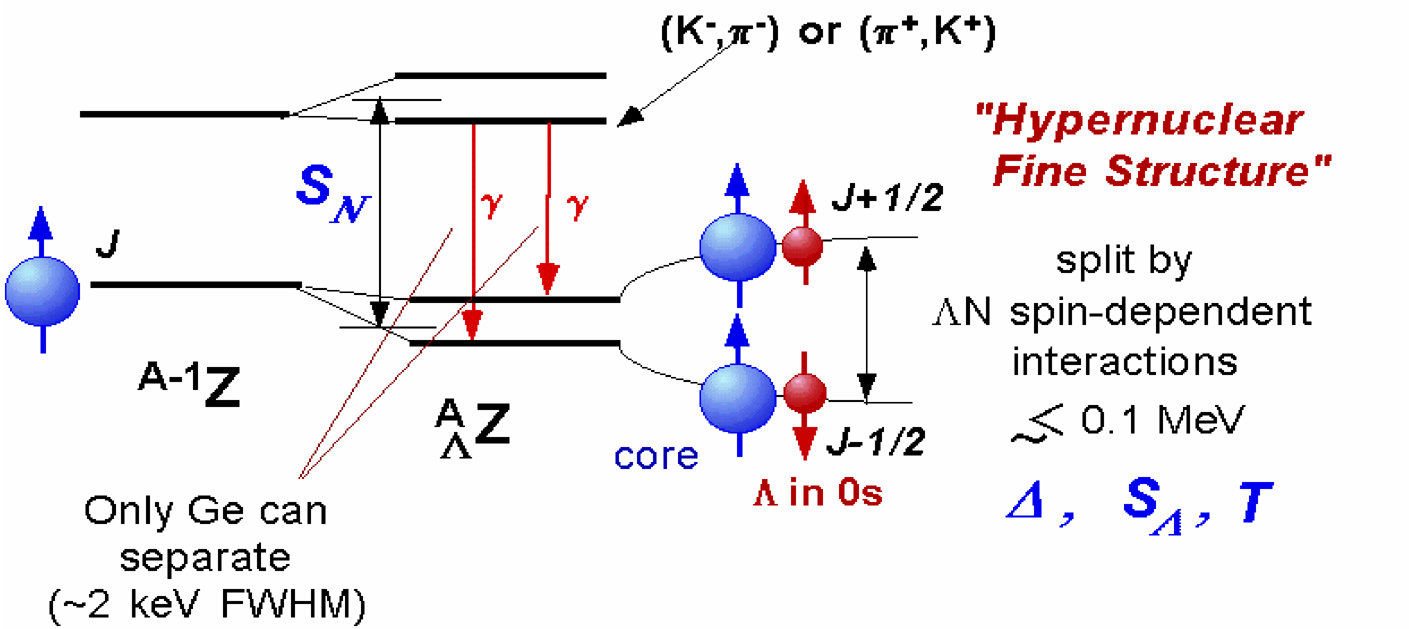
Few body calc.

Shell model calc.

Hypernuclear data

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

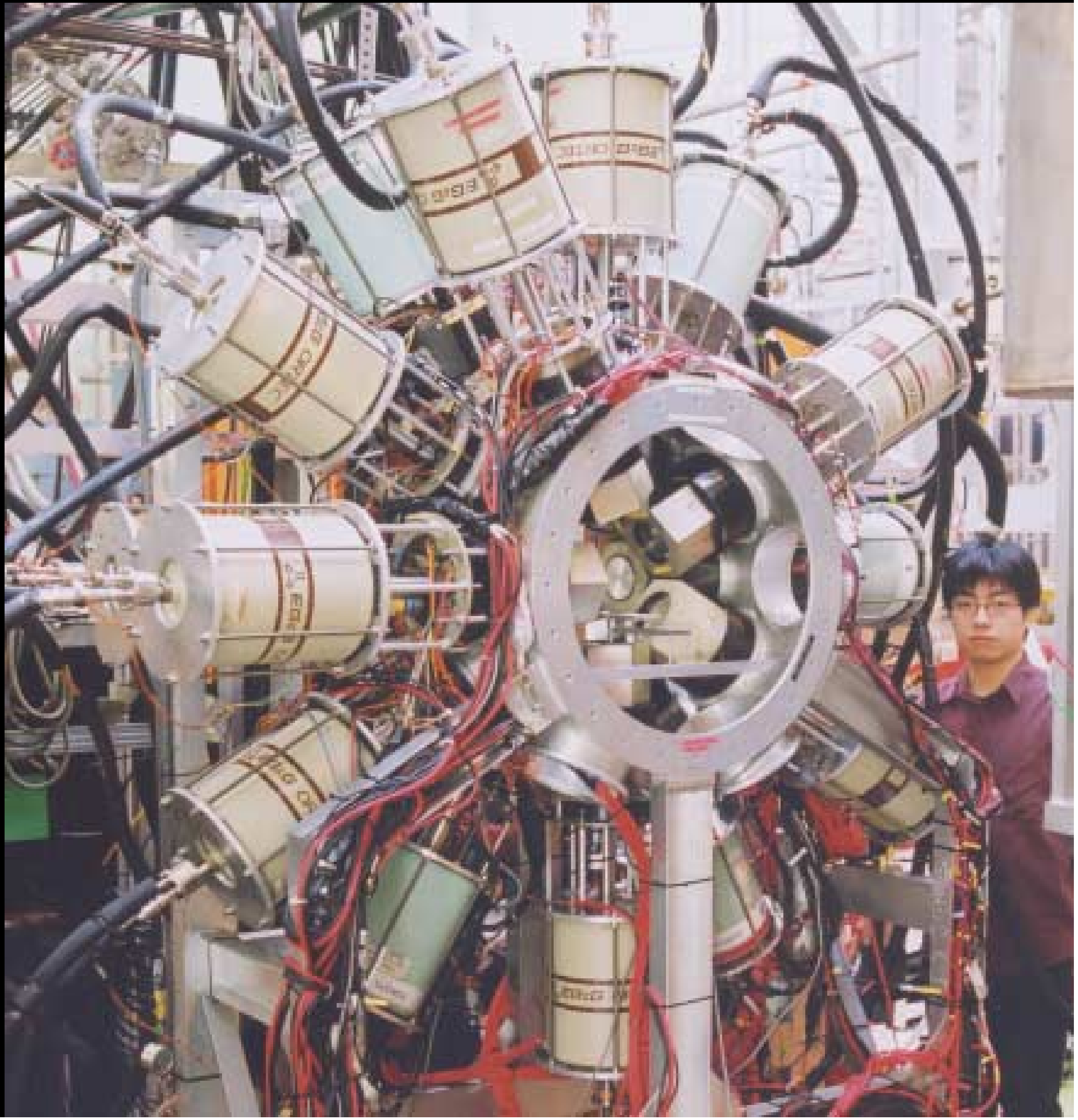
$$V_{\Lambda N}^{\mathrm{eff}} = V_0(r) + \underset{\Delta}{V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N} + \underset{S_\Lambda}{V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda} + \underset{S_N}{V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N} + \underset{T}{V_T(r)\, S_{12}}$$

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

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

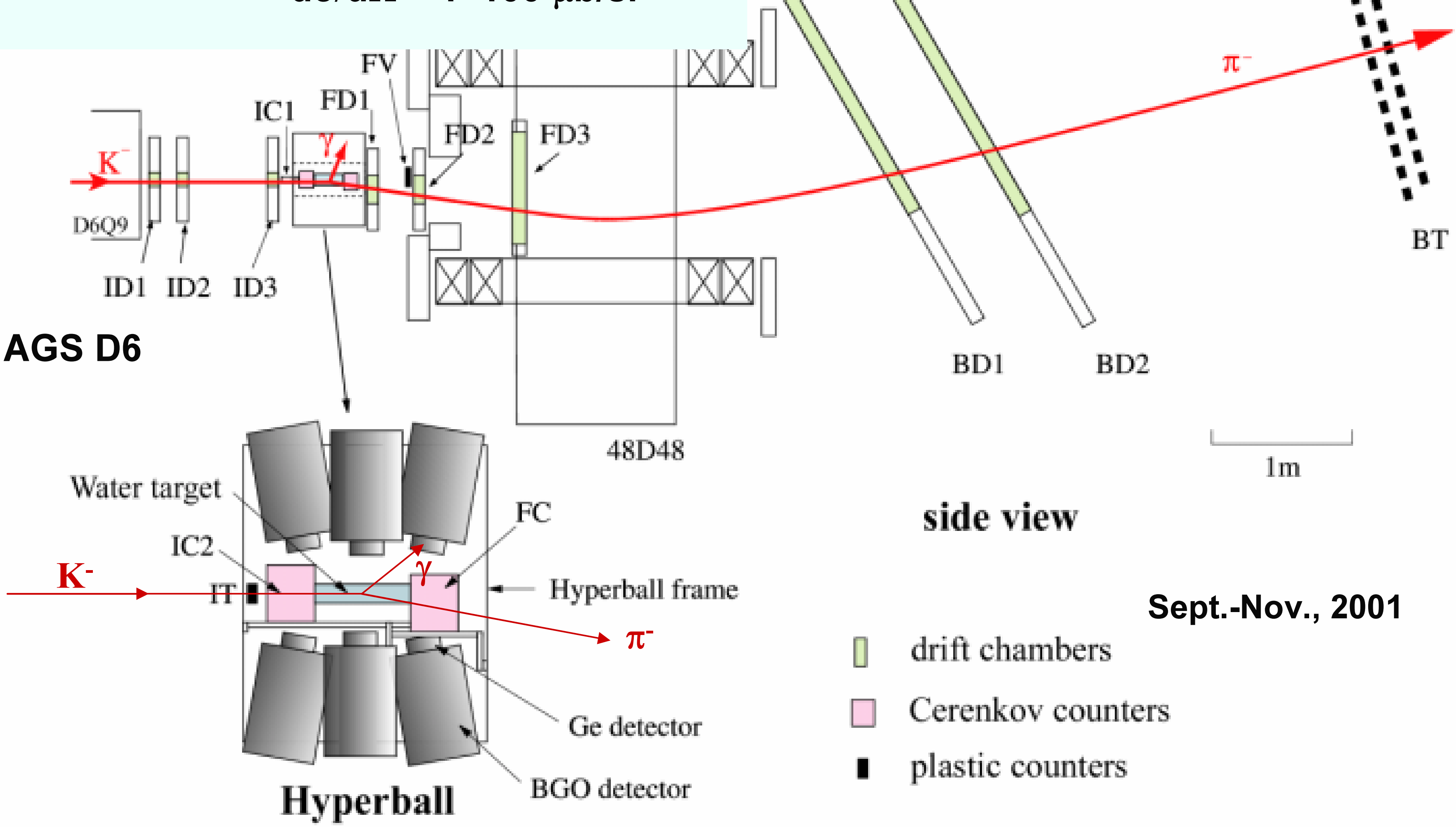


BNL-AGS: 24 GeV p, 2×10^{13}/spill
-> 0.9 GeV/c K^-, 2×10^5/spill

Hypernuclear production by $K^- n \rightarrow \Lambda \ \pi^-$
$d\sigma/d\Omega \sim 1$–$100 \ \mu b/sr$

E930 Setup

$^{A}Z \ (K^-, \pi^- \gamma) \ ^{A}_{\Lambda}Z$



AGS D6

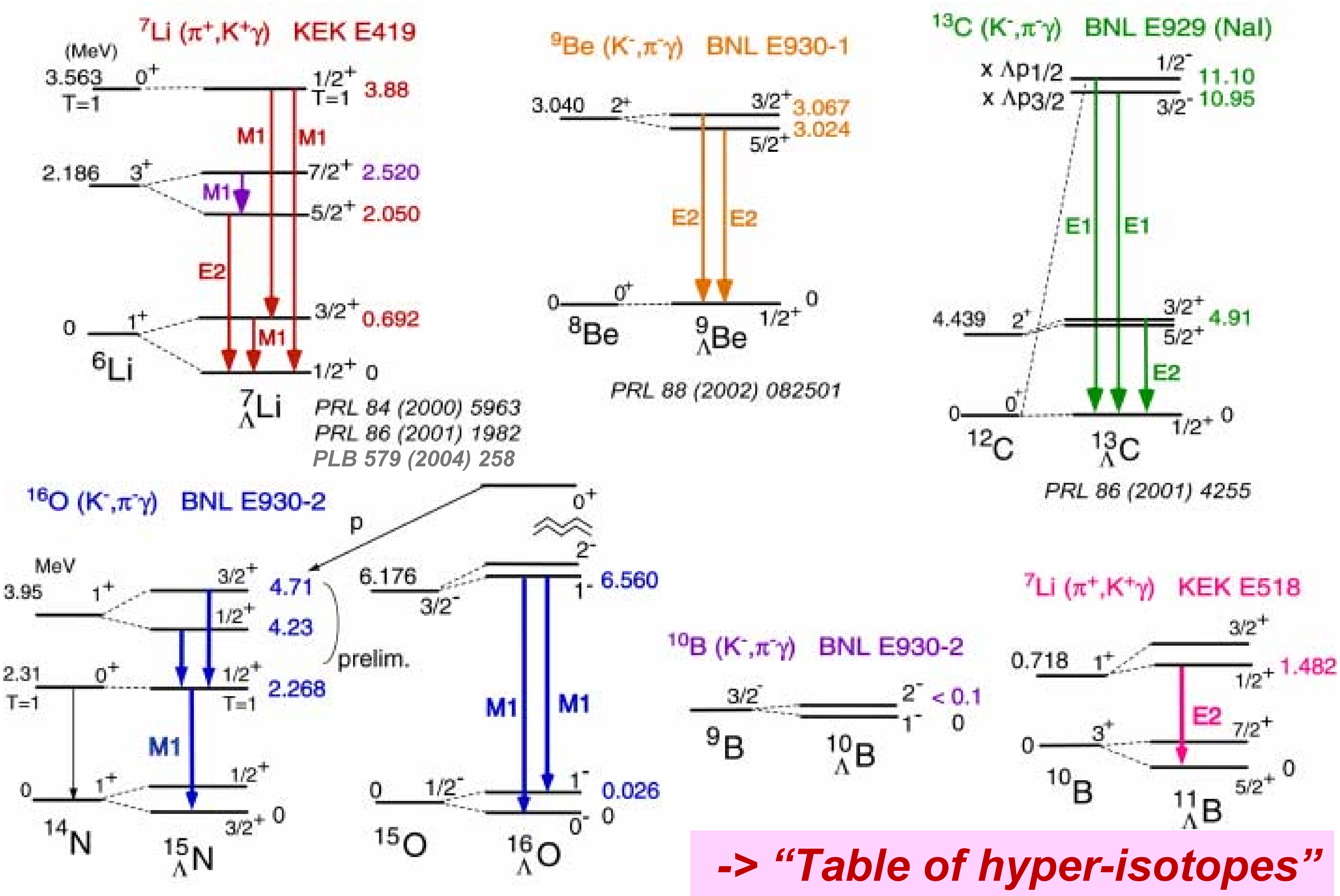
Sept.-Nov., 2001

drift chambers

Cerenkov counters

plastic counters

Present status

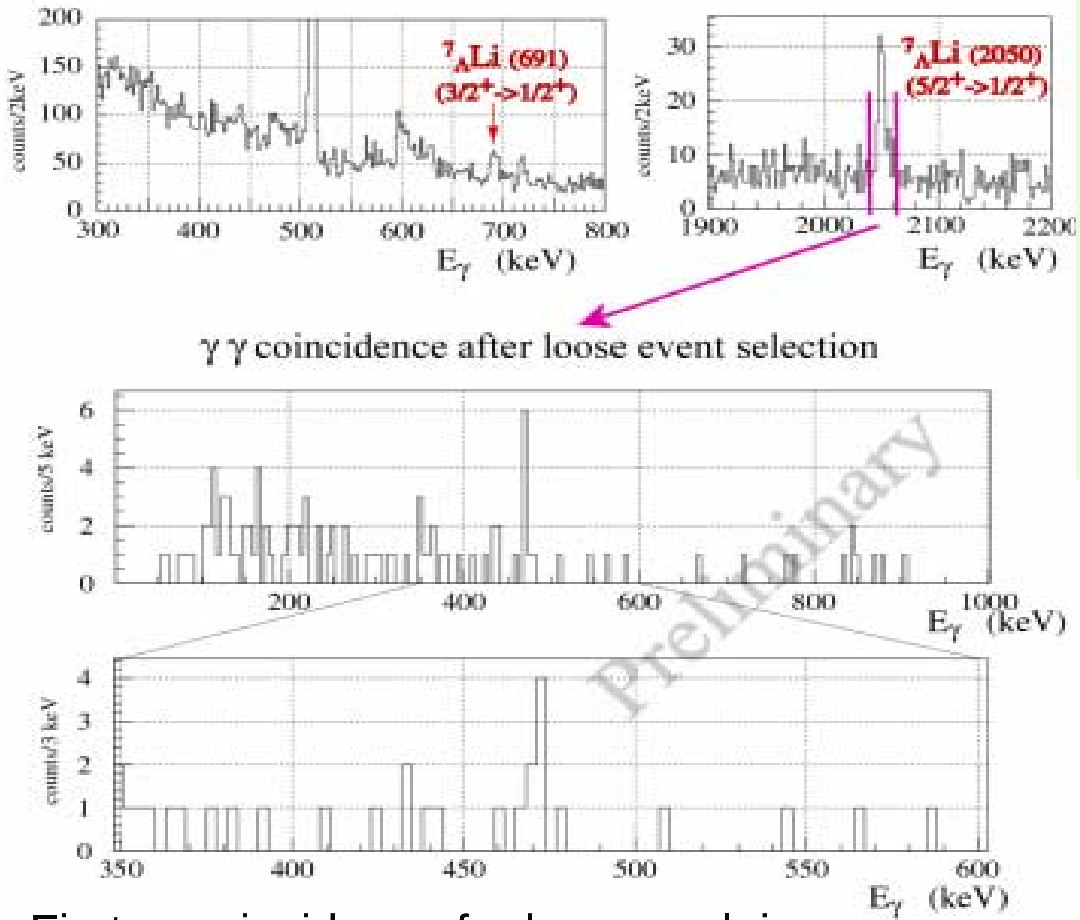


-> "Table of hyper-isotopes"

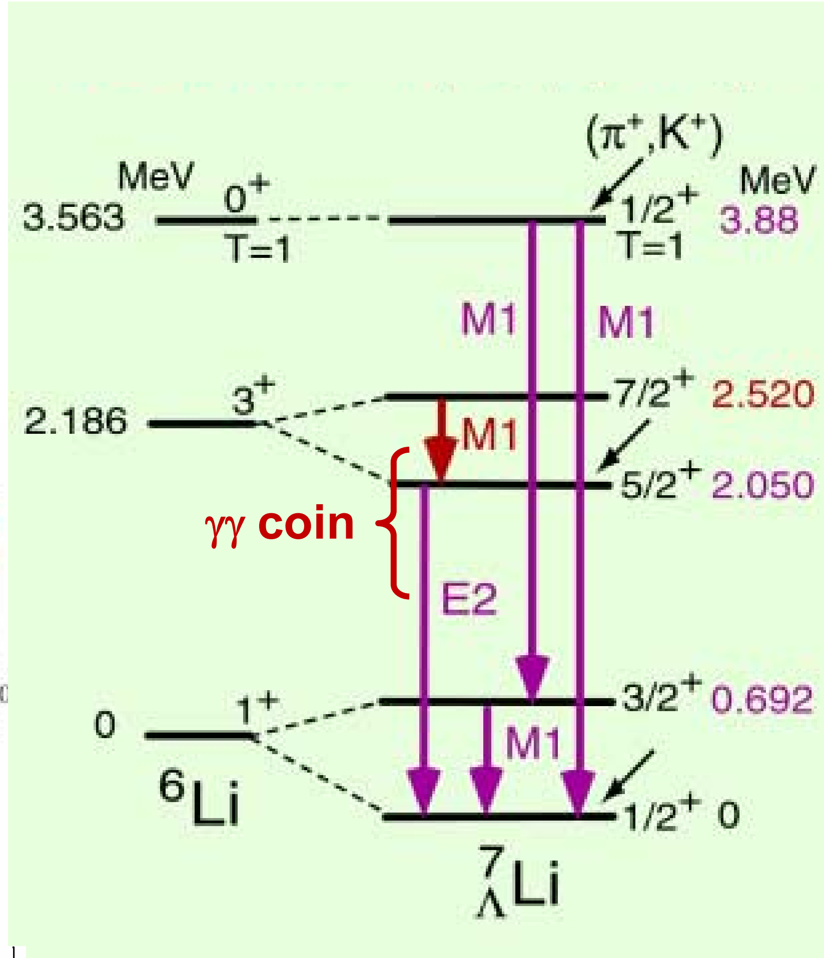
$^{7}_{\Lambda}$Li
Best-studied Hypernucleus

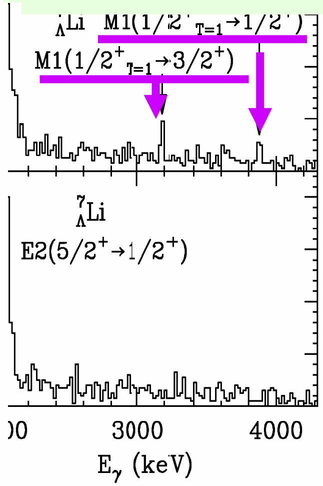
BNL E930('01)

^{10}B (K^-,$\pi^-\gamma$) $^{10}_{\Lambda}$B*(3^+) -> $^{7}_{\Lambda}$Li +^{3}He



First γγ coincidence for hypernuclei

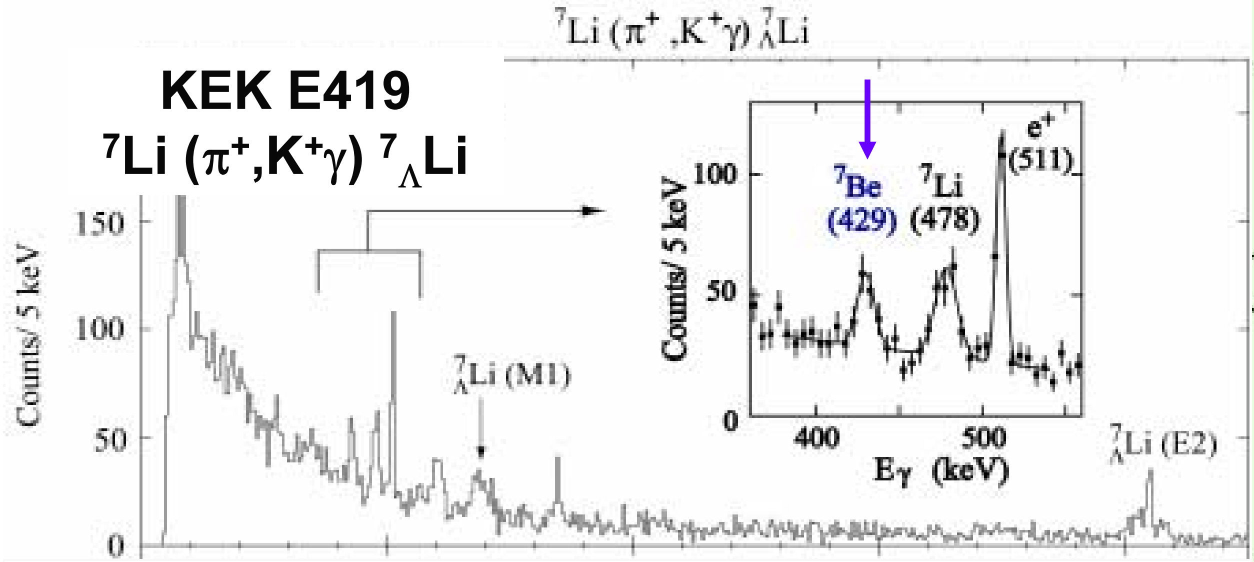


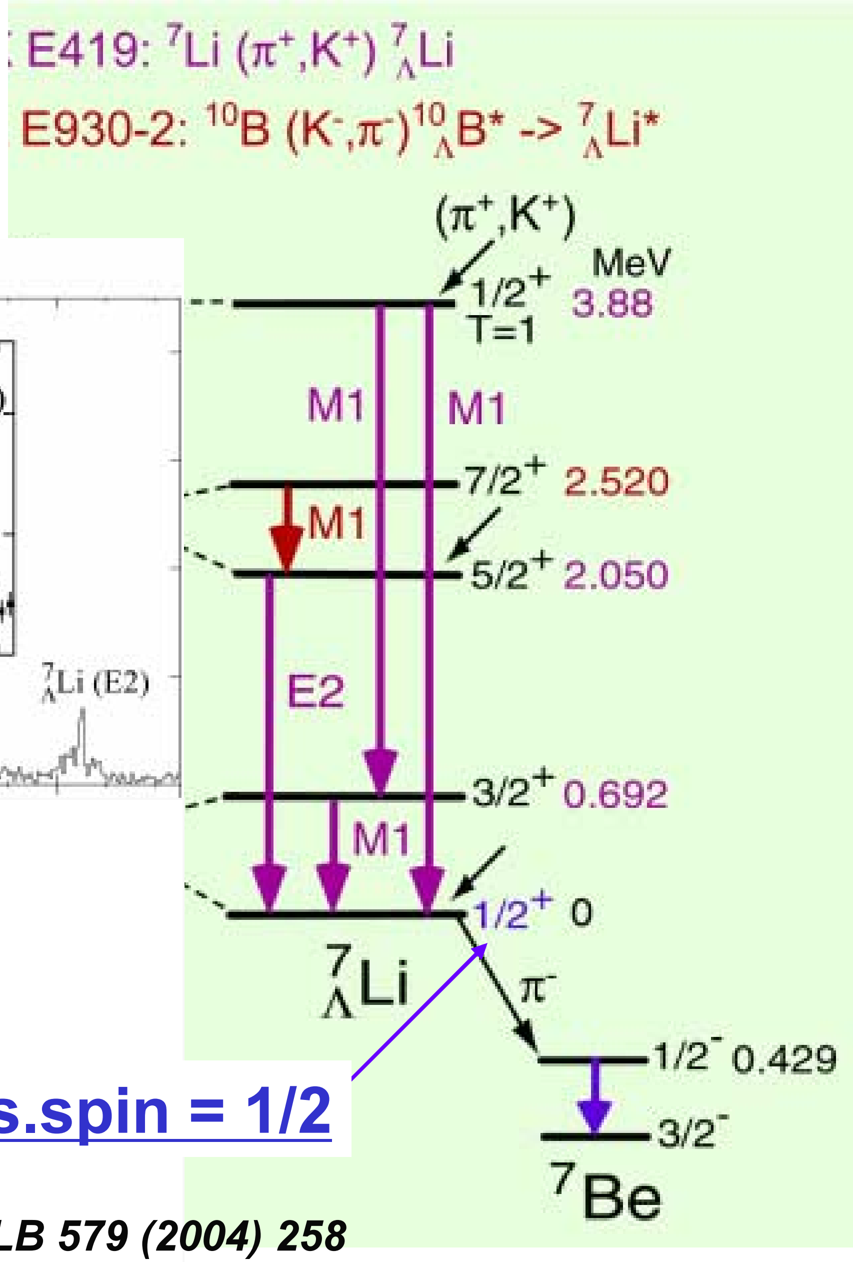


$^{7}_{\Lambda}$Li
Best-studied Hypernucleus

KEK E419

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





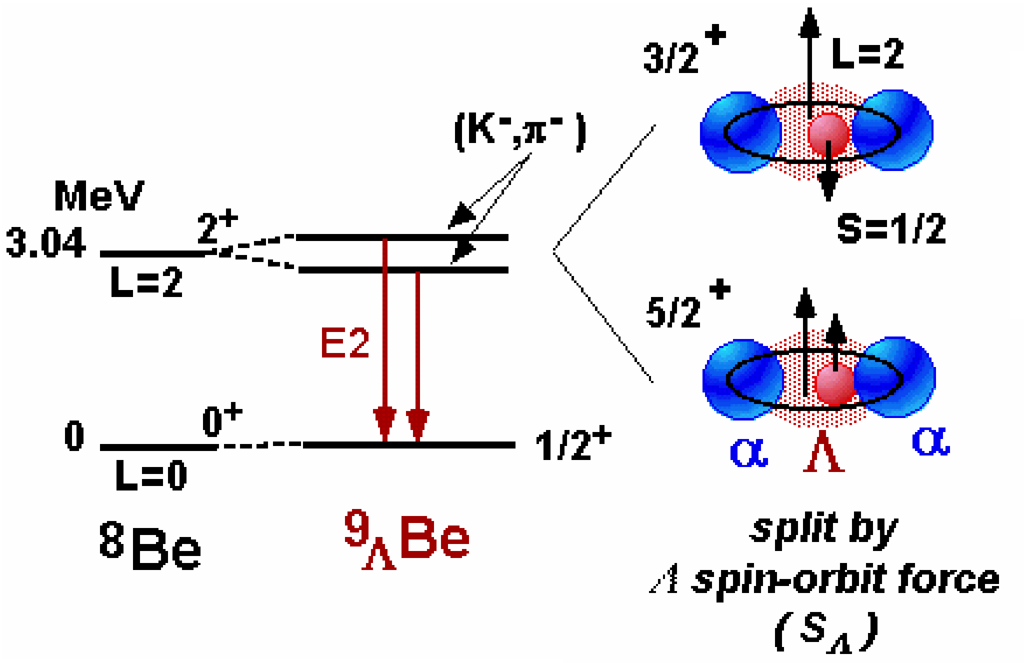
Non-spin-flip in weak decay Λ ->N π

$^{7}_{\Lambda}$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

$^{9}_{\Lambda}$Be
ΛN spin-orbit force



BNL E930('98)

- <u>Hiyama et al</u>: *PRL 85 (2000) 270*

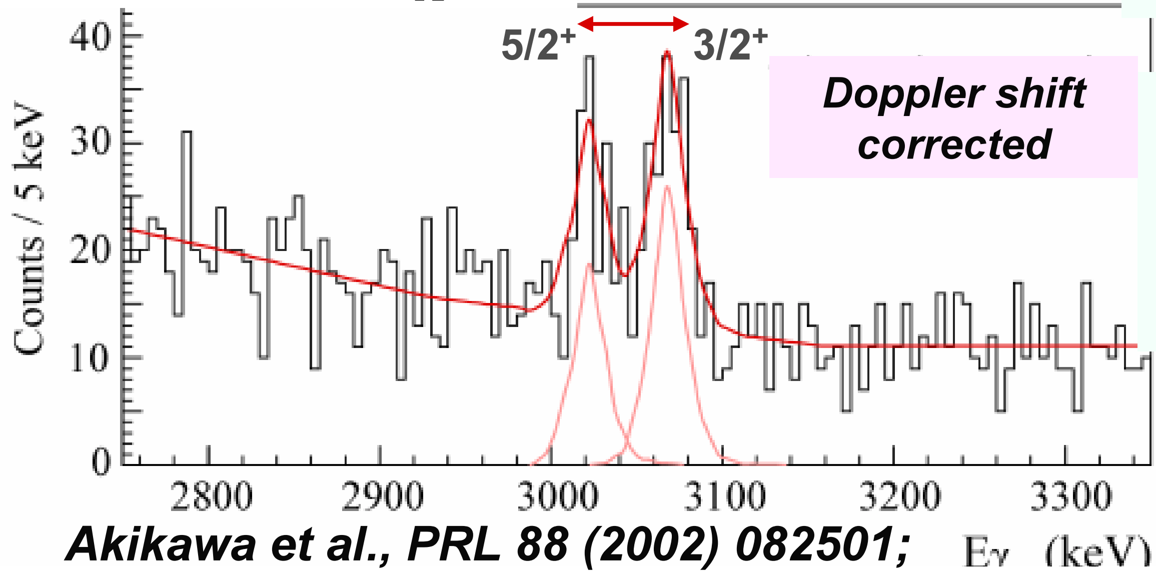
E(3/2+)-E(5/2+)

Meson exch. 0.08 - 0.20 MeV

Quark model 0.035 - 0.040 MeV

-> Favors quark models

^{9}Be (K^{-}, π^{-} γ) $^{9}_{\Lambda}$Be 43±5 keV



Akikawa et al., PRL 88 (2002) 082501;
Tamura et al., HYP03

- <u>Millener</u>:

E(3/2+)-E(5/2+)

$= -0.035\,\Delta - 2.465 S_\Lambda + 0.936 T$

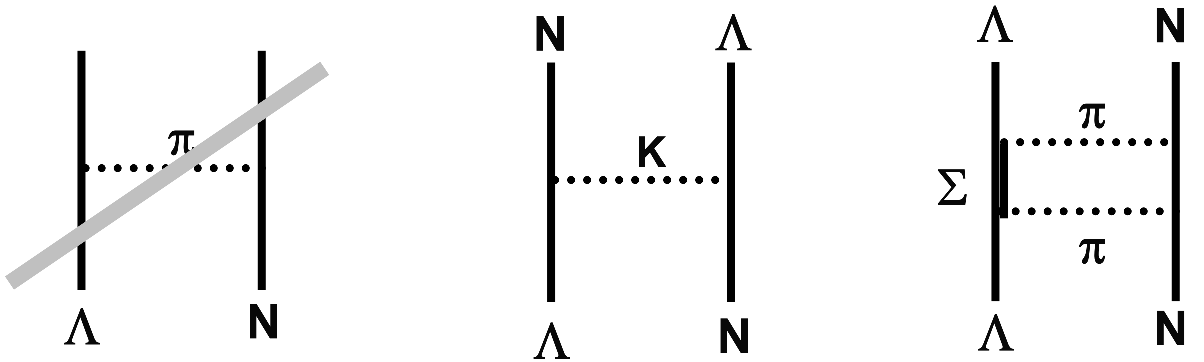
$S_\Lambda = -0.01$ **MeV**

Consistent with very small LS splitting in $^{13}_{\Lambda}$C

${}^{16}_{\Lambda}$O and ΛN tensor force

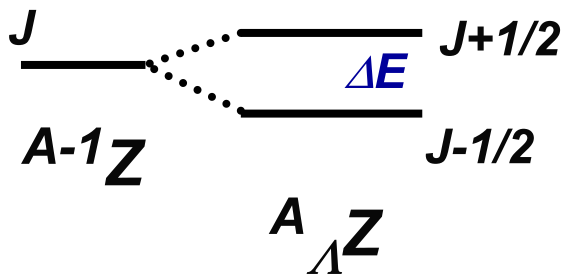
ΛN tensor force:

How is the nuclear tensor force without pion ?



Tensor force really very small?

Explained by meson exchange models?

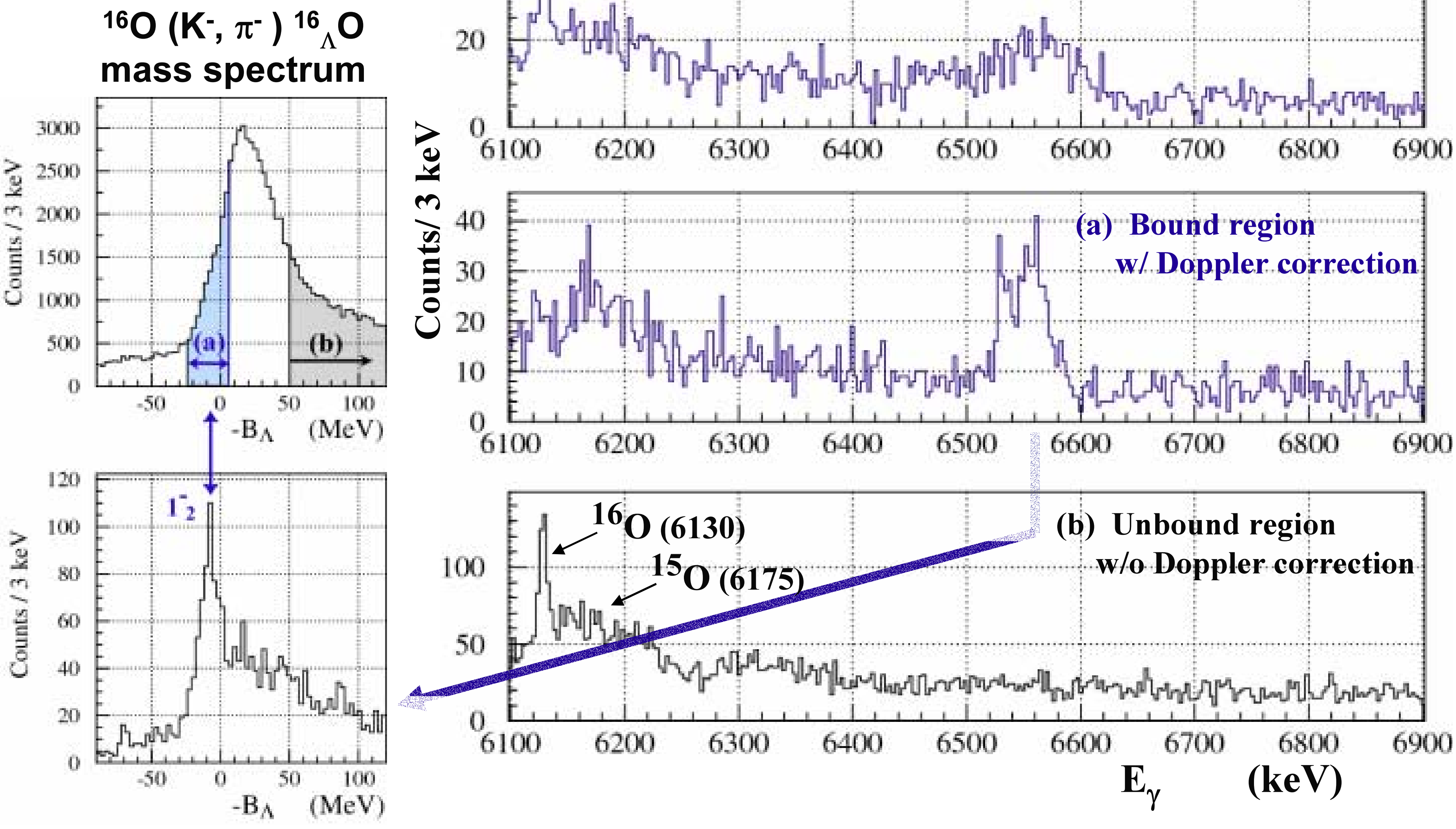


$p_{3/2}^{-1}s_{1/2}$ (${}^{12}_{\Lambda}$C) : $\Delta E = 2/3\,\Delta + 4/3\,S_{\Lambda} - 8/5\,T$

$p_{1/2}^{-1}s_{1/2}$ (${}^{16}_{\Lambda}$O) : $\Delta E = -1/3\,\Delta + 4/3\,S_{\Lambda} + 8\,T$

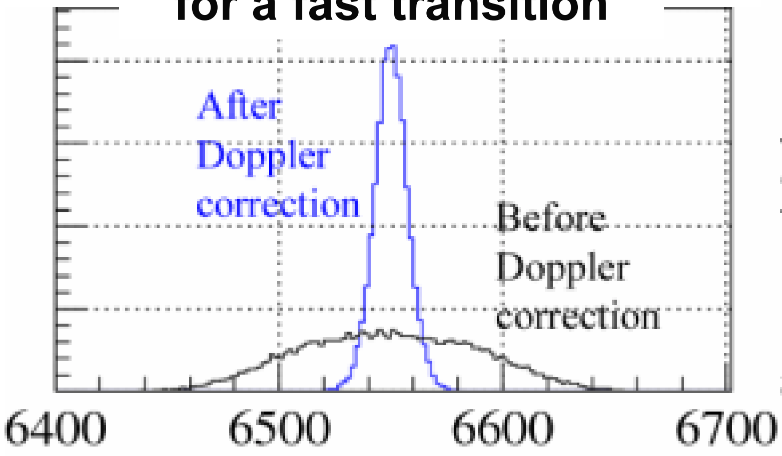
γ spectrum of $^{16}_{\Lambda}O$

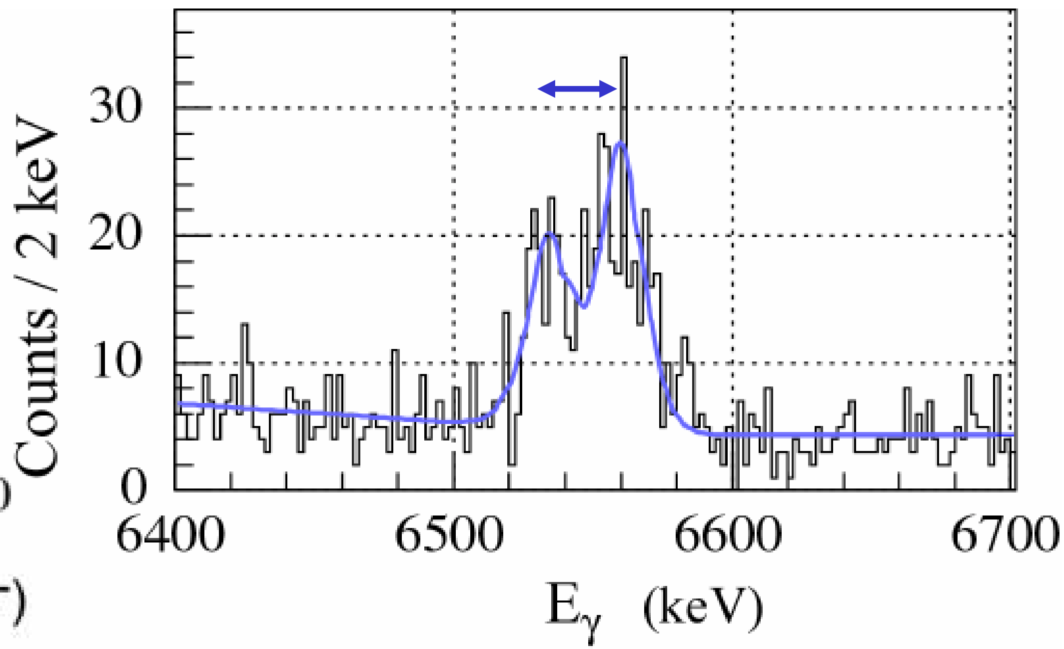
$^{16}O\,(K^-, \pi^- \gamma)\,^{16}_{\Lambda}O$

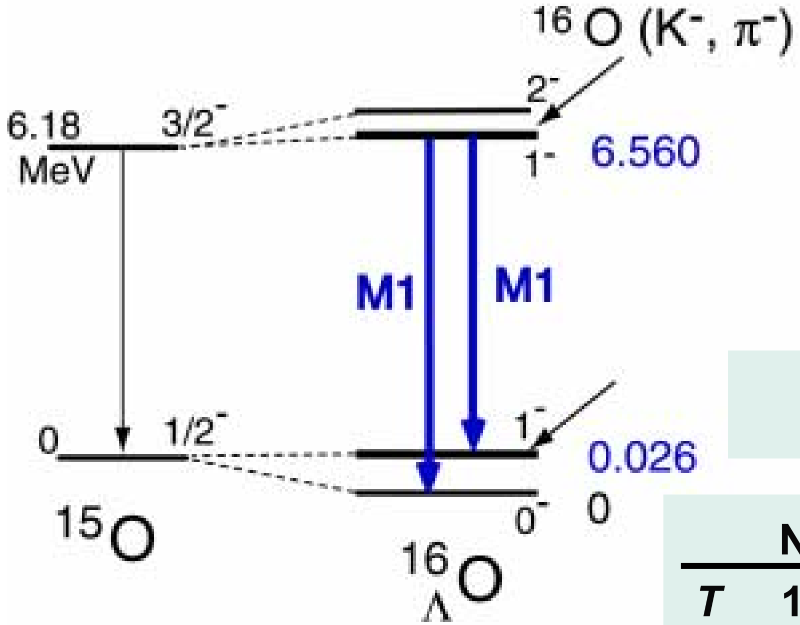


Fine structure of $^{16}_{\Lambda}$O and ΛN tensor force

Simulated peak shape for a fast transition







ΔE = 26.1 ± 2.0 keV (prelim.)

$E(1^-)-E(0^-)$ = $-0.39\,\Delta + 1.4\,S_\Lambda - 0.005\,S_N + 7.8\,T + \Lambda\Sigma$

(Millener, 2001)

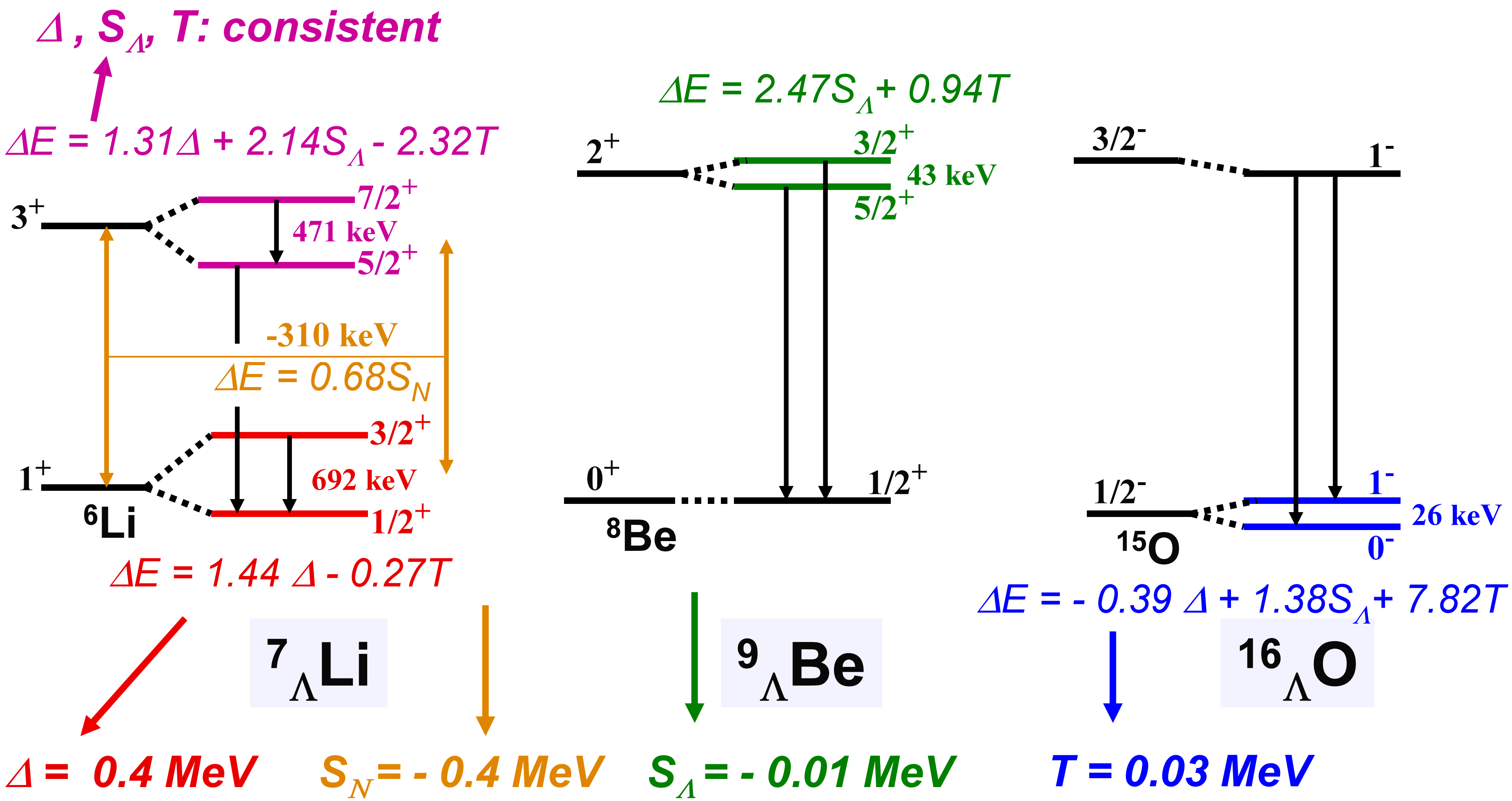
<- Δ = 0.46 MeV, S_Λ = -0.01 MeV

-> *T = 26 –32 keV* First info. on T

	ND	NF	NSC89	NSC97f
T (keV)	18	33	36	54

Some of Meson Exchange model predictions agree

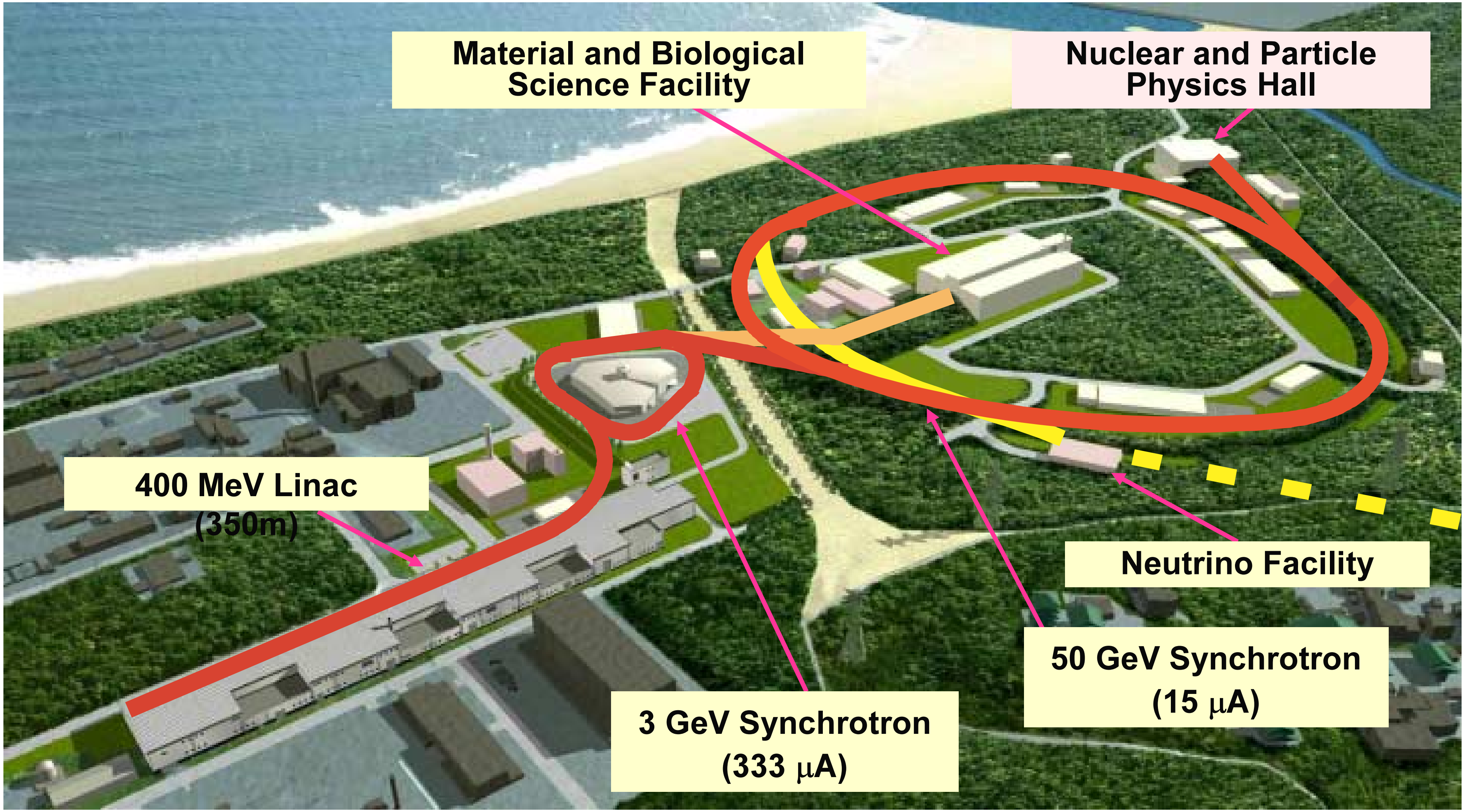
Hypernuclear Fine Structure



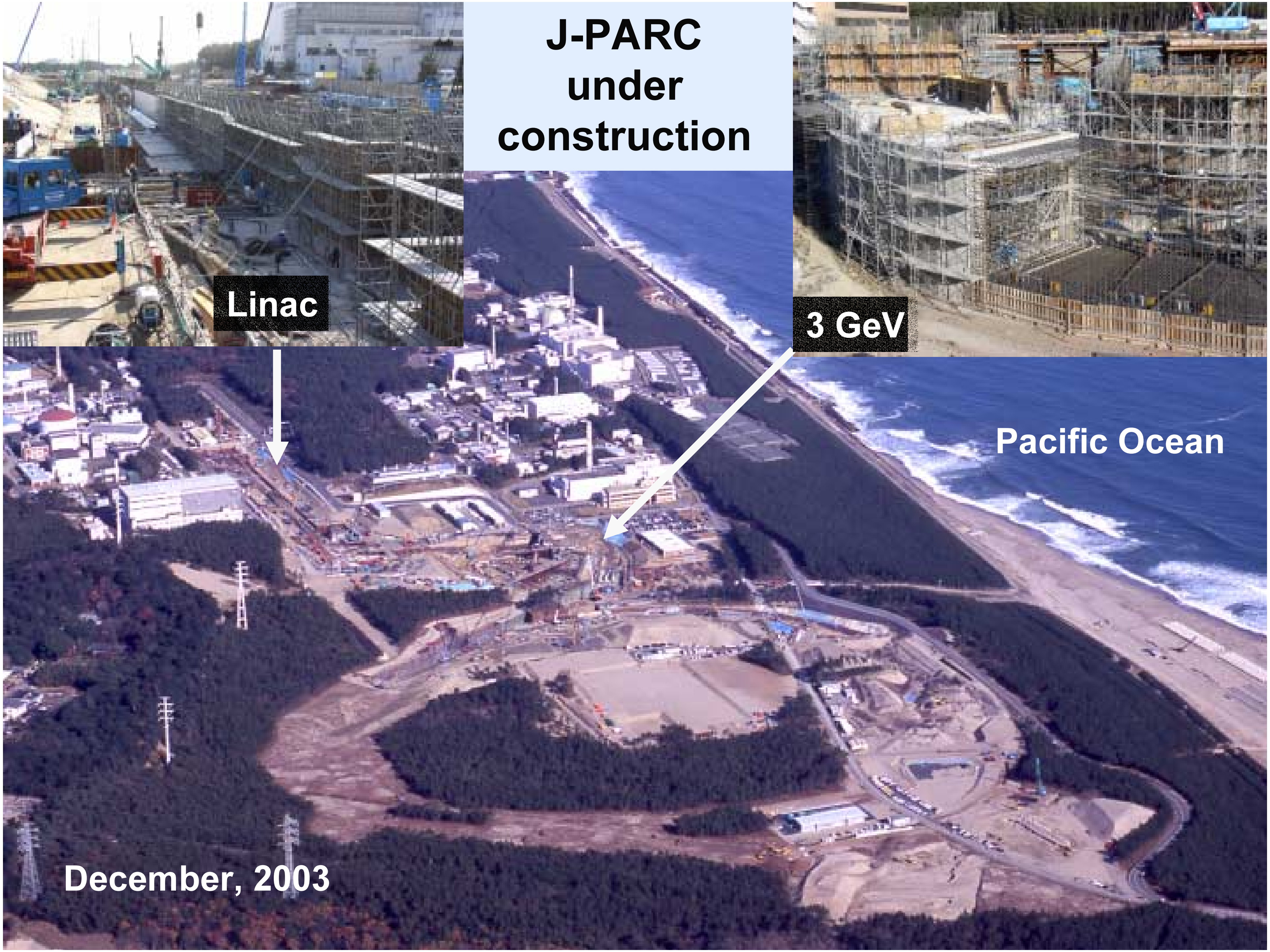
All the spin-dependent force parameters determined.

<u>J-PARC</u> (Japan Proton Accelerator Research Complex)

By KEK+JEARI, completed in 2008 at Tokai, Japan

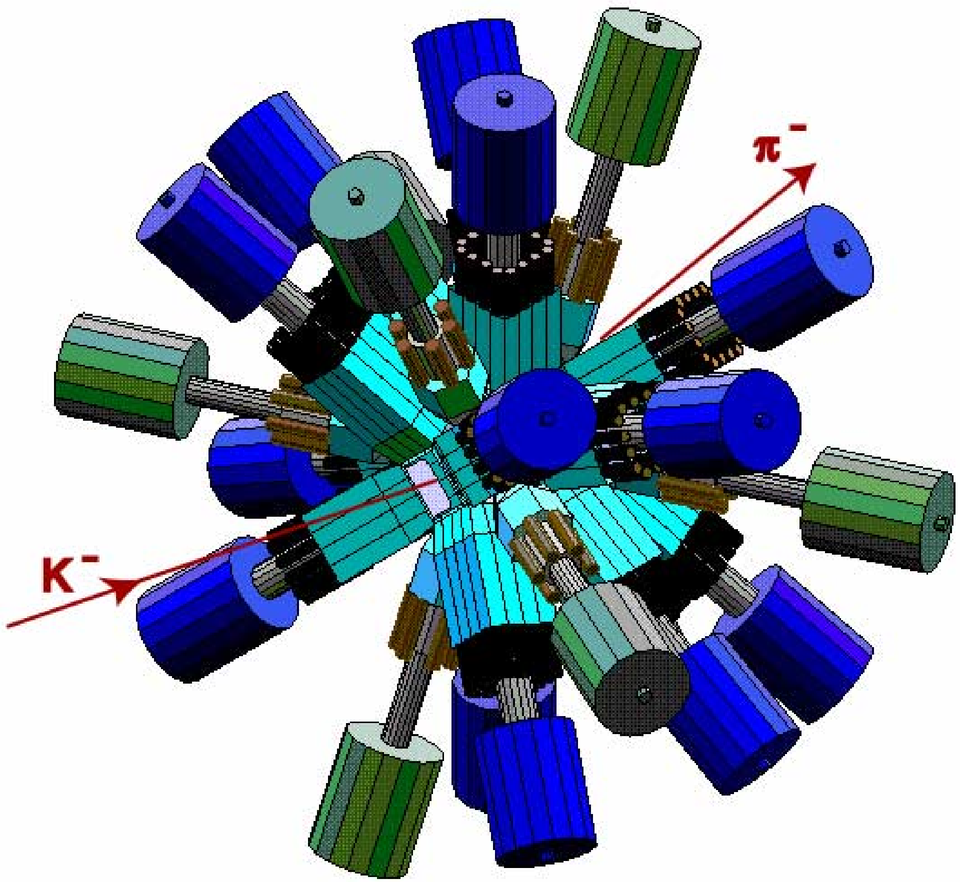


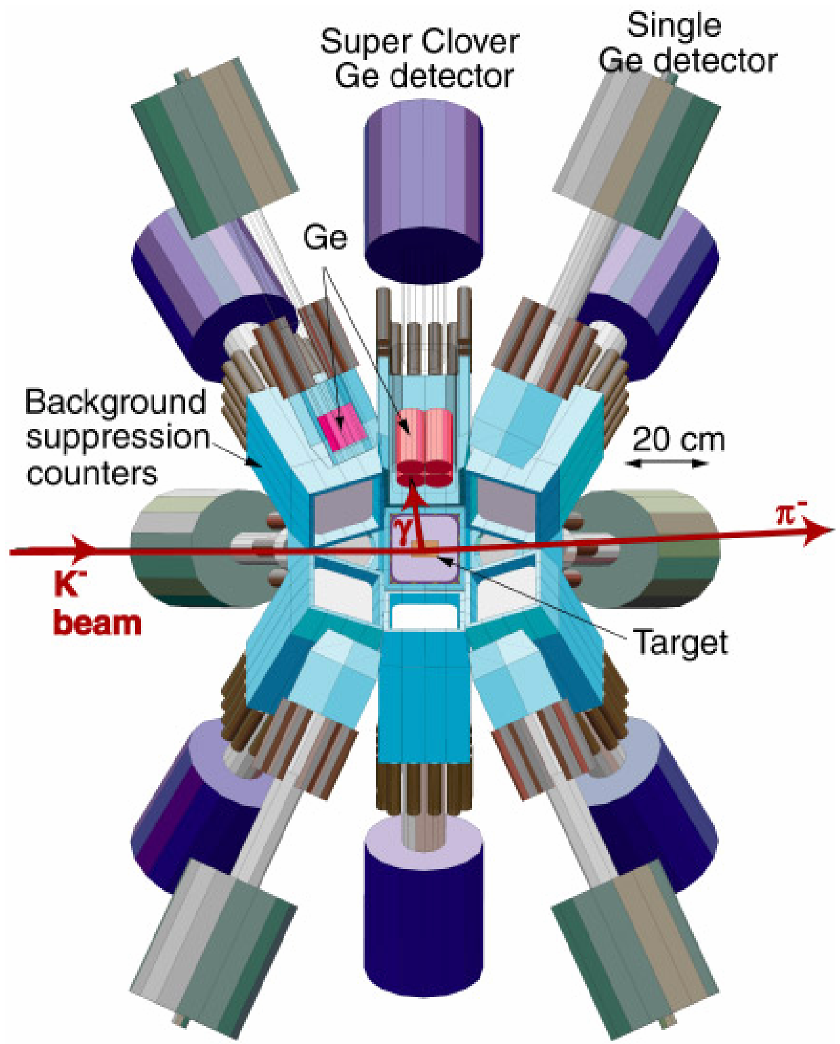
J-PARC under construction



Hyperball-J

New Hyperball for J-PARC





Bottom half viewed from top

- ε ~ 10% at 1 MeV (x4 of Hyperball)
- Rate limit: 500 kHz per each Ge (x5)
- K beam: ~ x100

=> Yield: x400 for single γ
x8000 for $\gamma\gamma$

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

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

μ_Λ in nuclei (ρ-dependence)

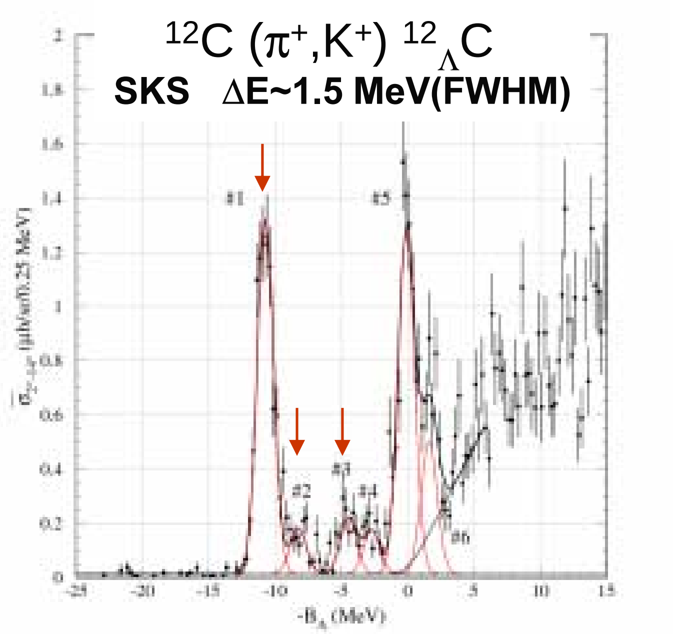
(5) Double strangenss (Ξ^- atom X rays and $\Lambda\Lambda$-hypernuclei)

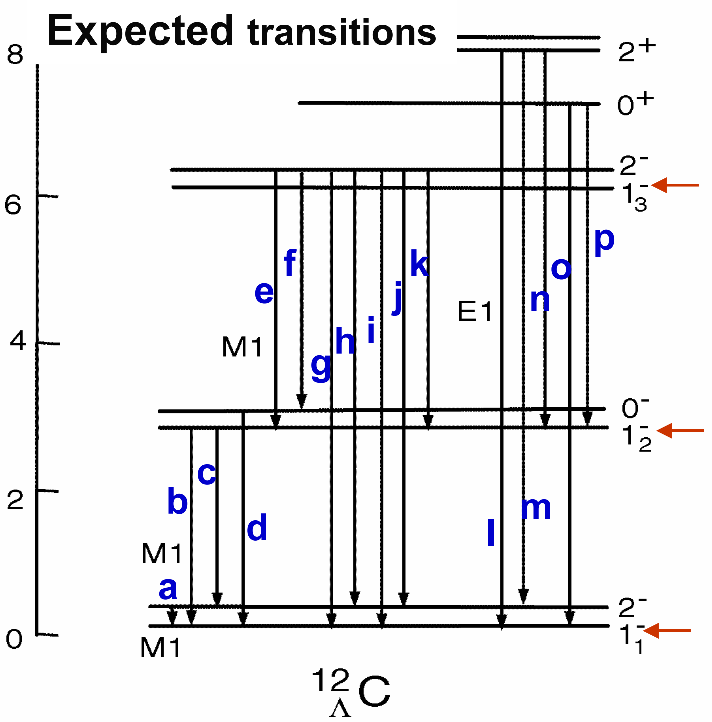
(K^-, $K^+\gamma$)

ΞN, $\Lambda\Lambda$ interactions

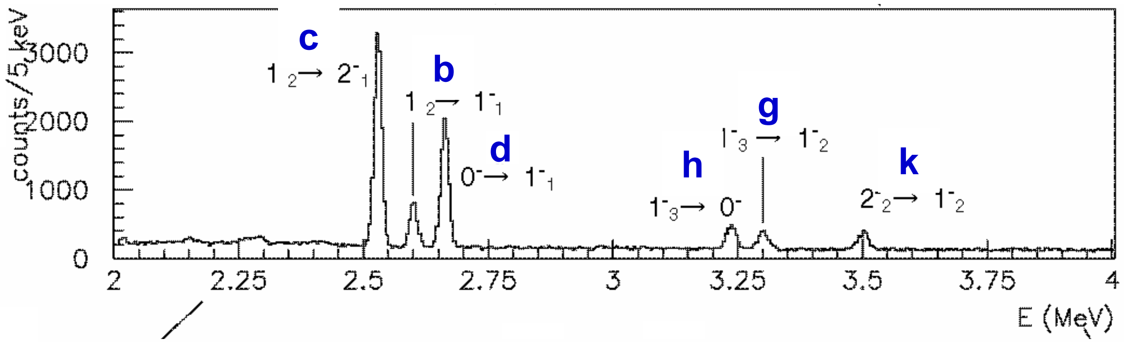
Light hypernuclei

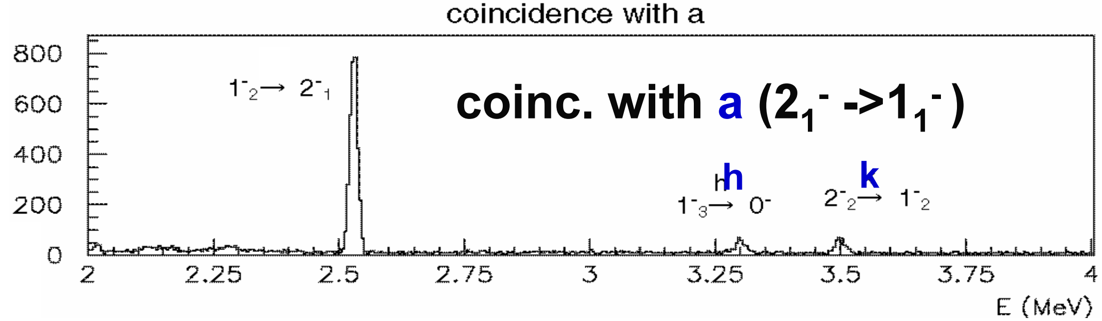
--- example of $^{12}_{\Lambda}C$



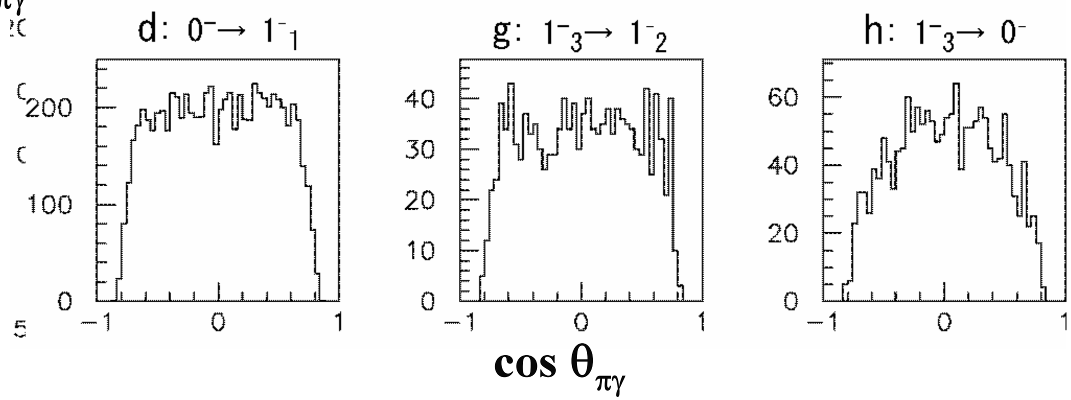


Simulation: K1.1, 10g/cm², 120 hours, Hyperball-J



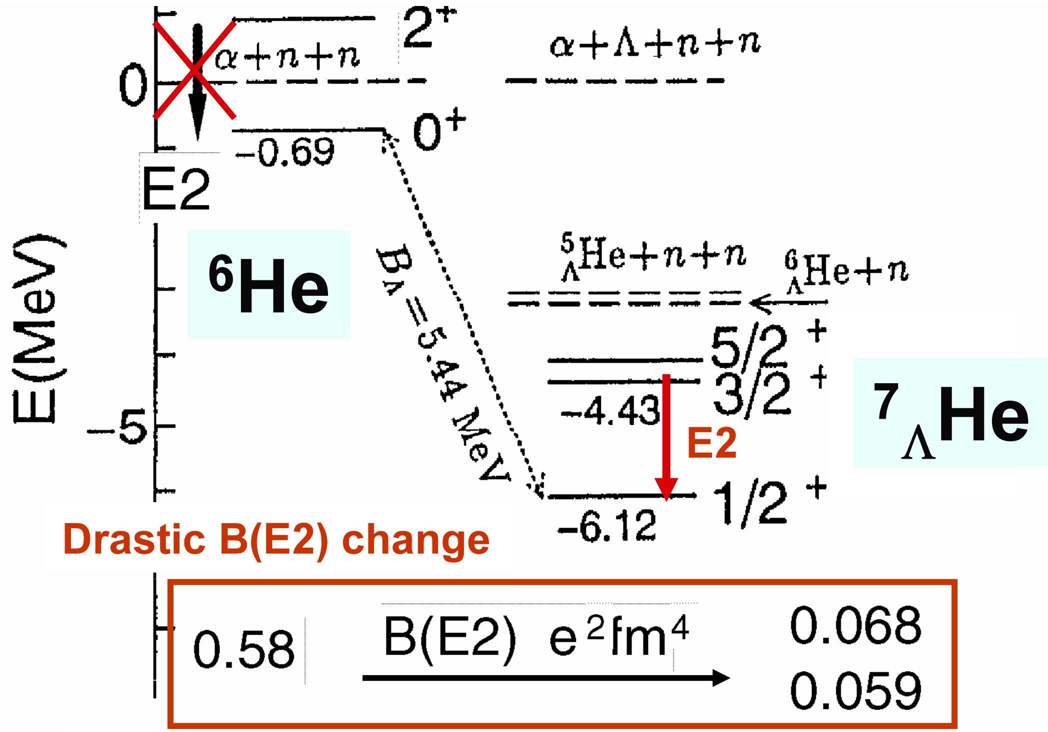


$\theta_{\pi\gamma}$ angular correlation -> spin assignment

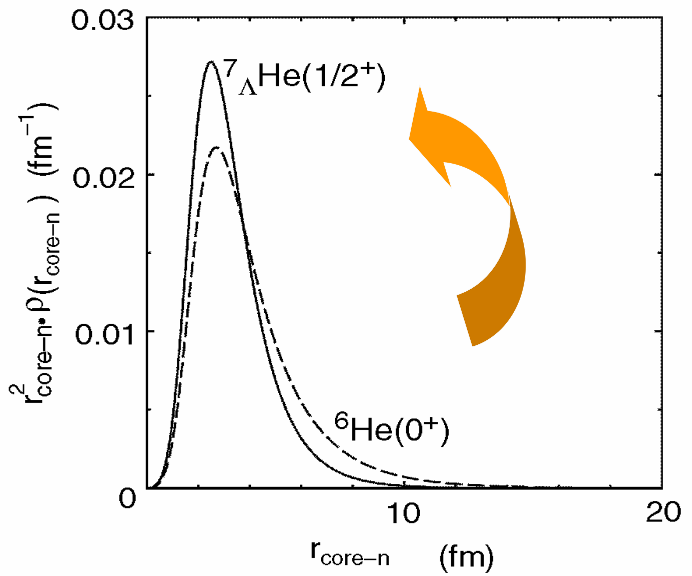


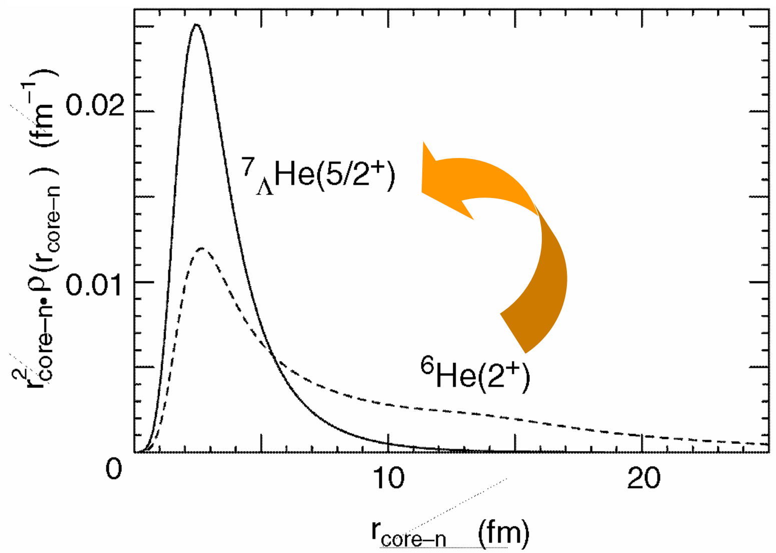
n-rich hypernuclei by (K^-,π^0) reaction

--- Disappearence of n-halo in $^7_\Lambda$He



Calc. by Hiyama





AGATA(500kHz) at J-PARC?

-> ε_γ x 5, $\varepsilon_{\gamma\gamma}$ x 25 of Hyperball-J

New experimental possibilities open.

- Impurity effect of Λ:
  Change of deformation, collective motions, ..
  Shrinkage by $\Lambda\,\Lambda$ -> Density of strange nuclear matter

- Various n-rich hypernuclei such as ${}^{11}_{\Lambda}$Li, ${}^{12}_{\Lambda}$Li
  (K^-,π^+) ~ nb/sr ^{11}B (K^-,π^+) ${}^{11}_{\Lambda}$Li (Λ makes ^{10}Li bound)
  K^- -in-beam: $(K^-,\gamma\gamma)$ ${}^{12}_{\Lambda}$Li

- Systematic spectroscopy of various $\Lambda\Lambda$ hypernuclei
  Z (K^-, K^+) ${}_{\Xi}$[Z-2] -> ${}_{\Lambda\Lambda}$Z ' + ...

Summary

- **Hypernuclear γ spectroscopy with Hyperball in progress**
  -> ΛN interaction, shrinking effect from B(E2)
  First success of $\gamma\gamma$ coincidence

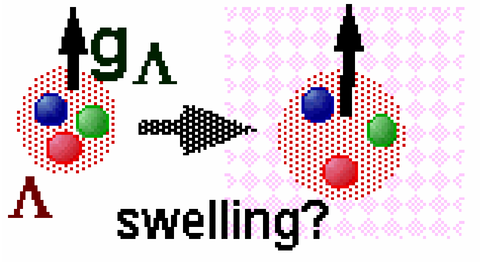
- **$^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, $^{16}_{\Lambda}$O : Hypernuclear fine structure**
  -> All the ΛN spin-dependent force parameters
  (Δ, S_Λ, S_N, T) determined.
  LS (S_Λ, S_N) quark picture favored
  Tensor (T) meson exchange OK

- **J-PARC high-intensity K beam + Hyperball-J (or AGATA)**
  -> "Table of Hyper-isotopes" incl. heavy, n-rich,.. hypernuclei
  AGATA will further extend possibilities.

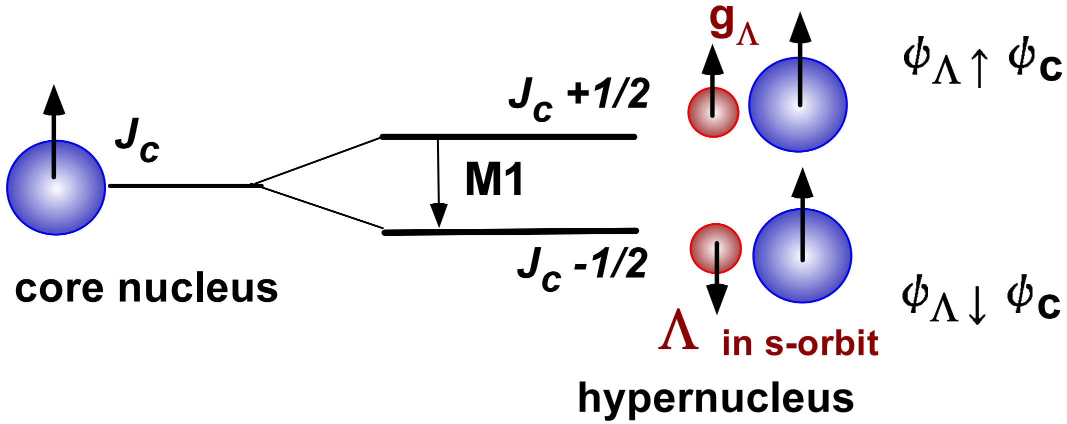
Λ-Spin-flip B(M1)

B(M1) ~ |<Φ

μ_Λ in nucleus -> medium effect of baryons



$$\frac{e\hbar}{2mc}\ ?$$

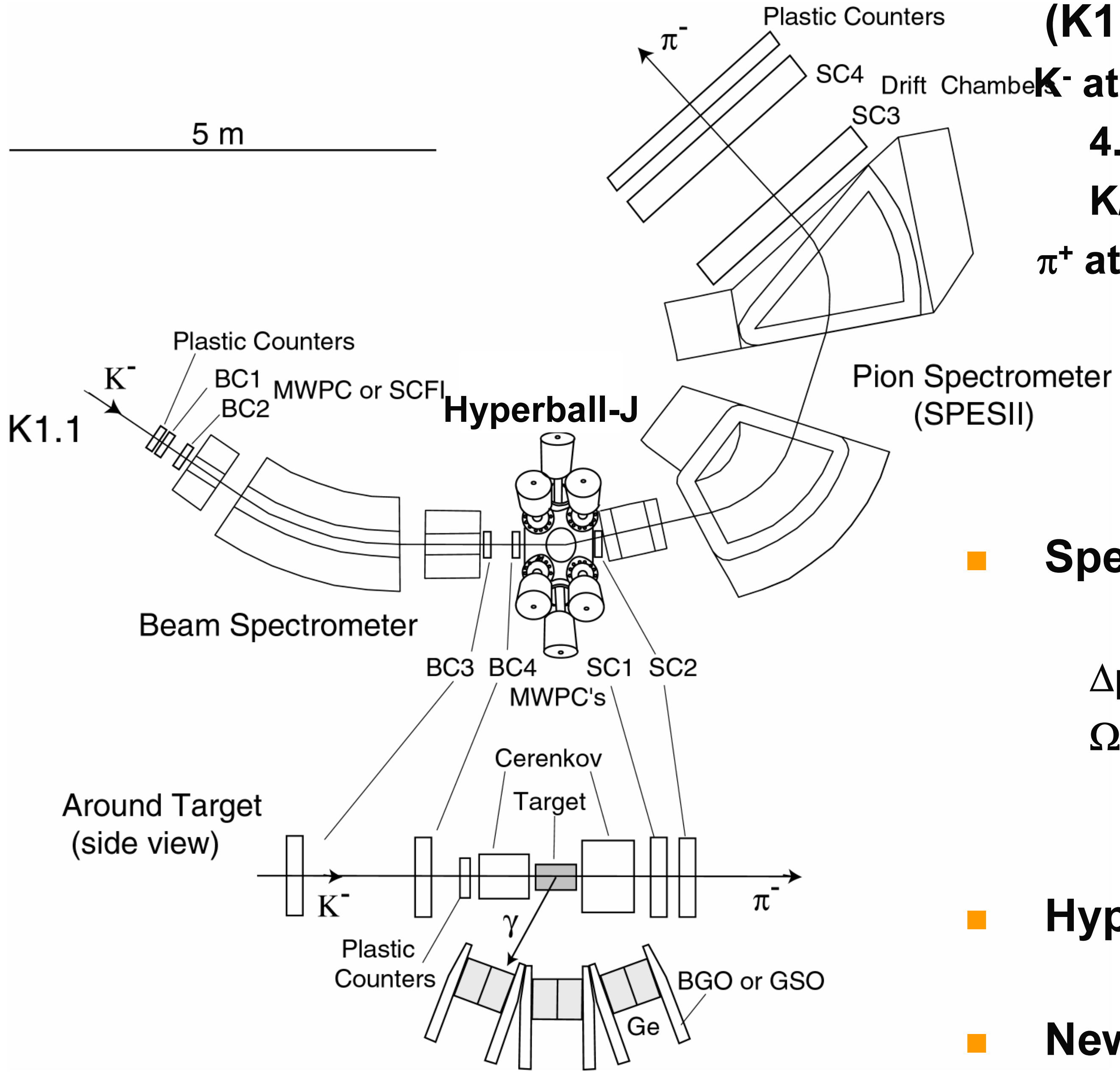


$$\mathrm{B(M1)} \propto |\langle \Phi_f | \mu^z | \Phi_i \rangle|^2$$
$$= |\langle \phi_{\Lambda\uparrow}\ \phi_c|\ g_c J_c^z + g_\Lambda J_\Lambda^z\ | \phi_{\Lambda\downarrow}\ \phi_c \rangle|^2$$
$$\propto (g_c - g_\Lambda)^2$$

- **Doppler shift attenuation method** *[same as B(E2), established]*
  (π^+,$K^+\gamma$), (K^-, $\pi^-\gamma$) for light hypernuclei
- **γ-weak coincidence method** *[new, only possible at J-PARC]*
  (K^-, $\pi^- p\gamma$) for heavy hypernuclei

Accuracy Δg_Λ < 5% achievable **-> ρ dependence of g_Λ**

Setup at K1.1



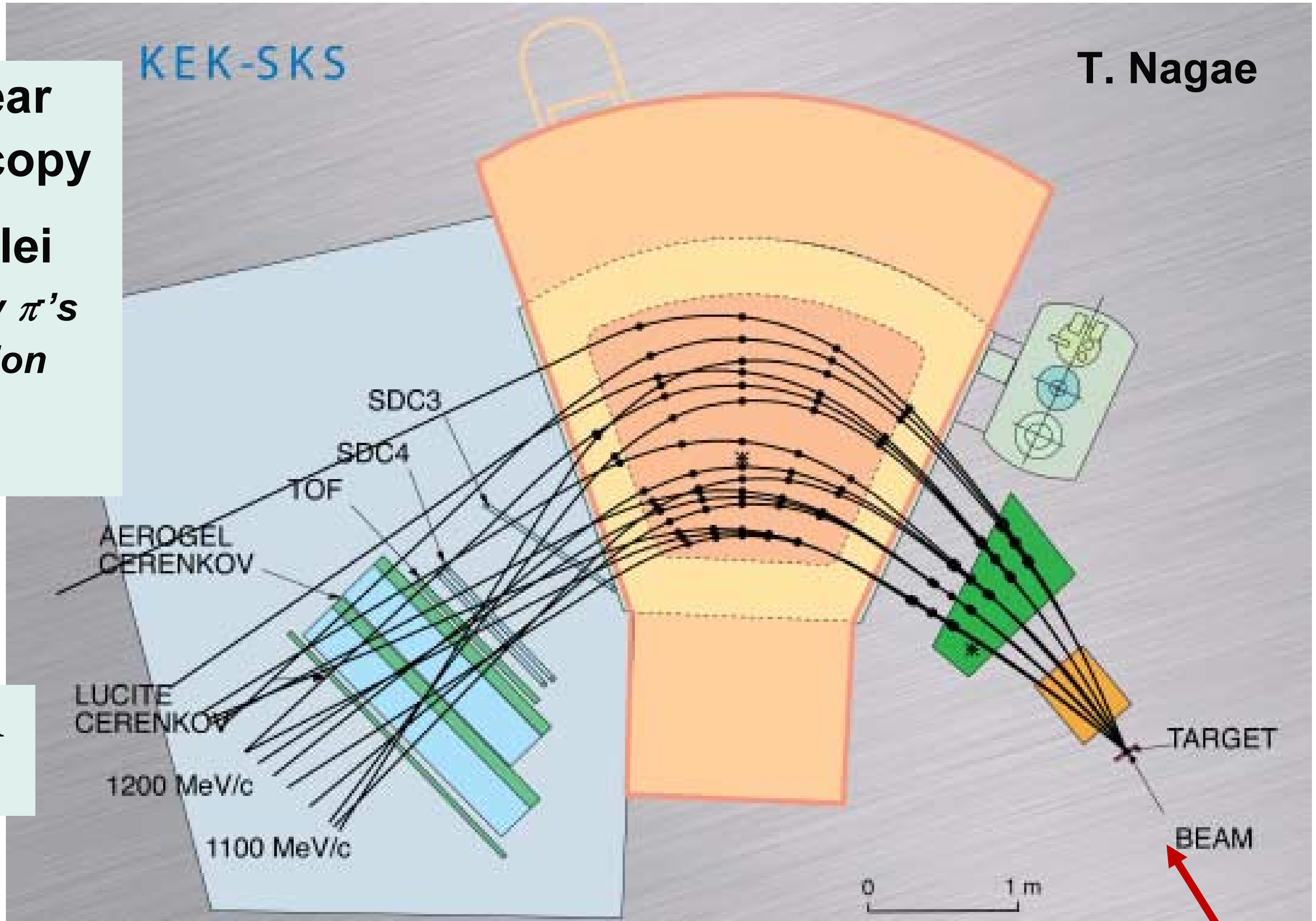
- **Beamline: K1.1 (K1.1BR)**
  K^- at 1.1, 0.8 GeV/c
  4.2×10^7 K^-/spill
  $K/\pi > 1$
  π^+ at 1.05 GeV/c
- **Spectrometer: SPESII (existing)**
  $\Delta p/p < 2$ MeV (FWHM)
  $\Omega \sim 20$ msr
- **Hyperball-J (2007?)**
- **New CDS**

(K$^-$,K$^+$) experiments with K1.8 + SKS

- Ξ hypernuclear spectroscopy
- $\Lambda\Lambda$ hypernuclei
  + *CDS for decay π's*
  hybrid emulsion
  weak decays
  γ rays

↓

ΞN, $\Lambda\Lambda$, ΞN-$\Lambda\Lambda$ interactions

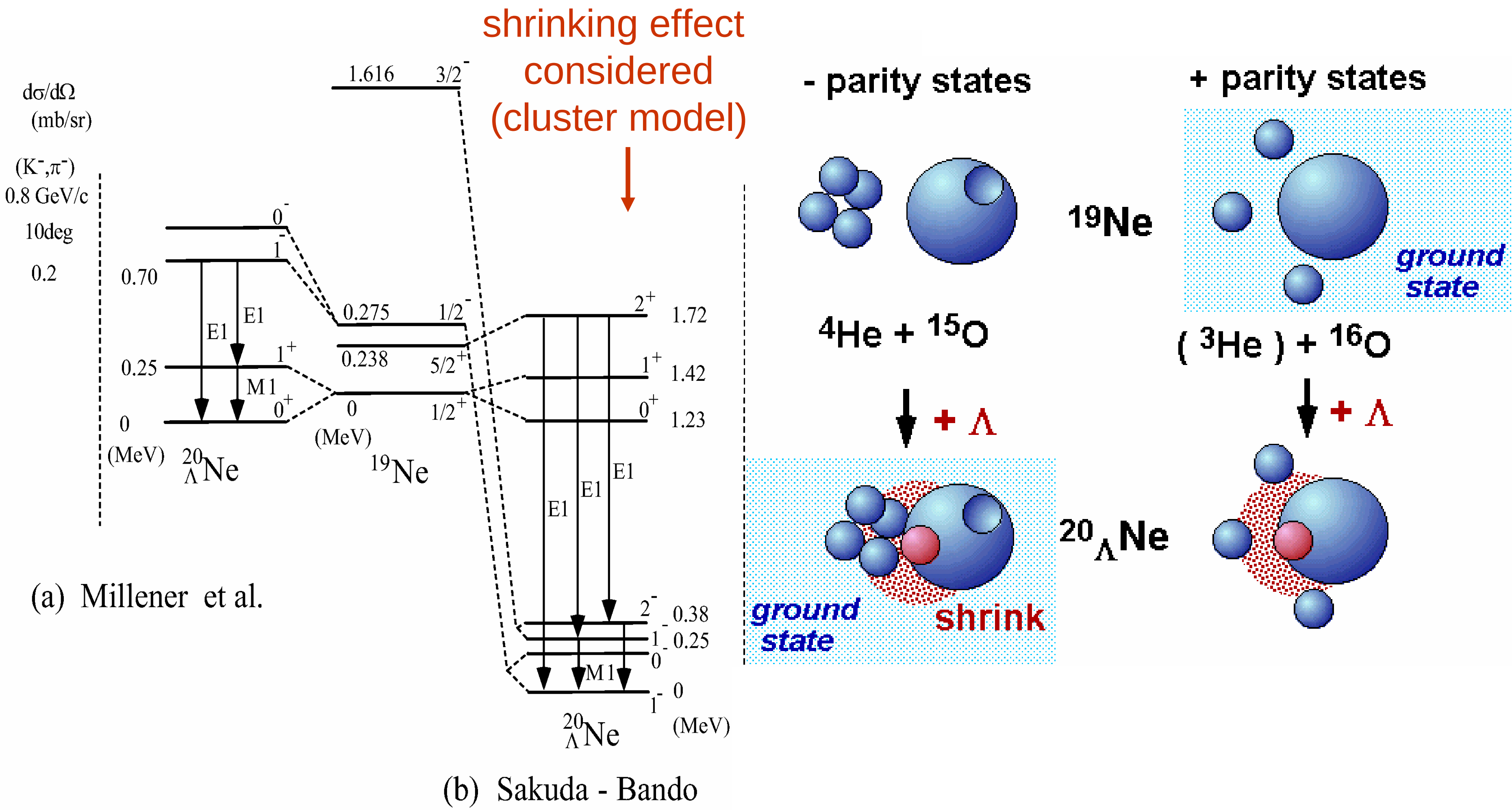


1.8 GeV/c K$^-$ beam
1.0x10^7/pulse

(1-b) Light hypernuclei

Impurity effect

--- example of $^{20}_{\Lambda}$Ne : change of cluster structure



Strangeness Nuclear Physics Experiments at J-PARC

Day-1 experiments

- *K1.8* ■ Ξ hypernuclear spectroscopy by (K^-,K^+)
- *K1.8* ■ $\Lambda\Lambda$ hypernuclei by sequential π decay method and by hybrid emulsion method
- *K1.1* *K1.8* ■ Precision γ spectroscopy of Λ and $\Lambda\Lambda$ hypernuclei, Ξ X-rays
- *HR* ■ High-resolution (π,K^+) spectroscopy for Λ, Σ, and n-rich Λ hypernuclei
- *K1.1* *K1.8* ■ Weak decays of Λ and $\Lambda\Lambda$ hypernuclei
- *K1.1* ■ K-nucleus bound states by (K^-,N) and (K^-,π) reactions
- *K1.1* *K1.8* ■ ΛN, ΣN, ΞN scattering experiments

Do we understand nuclear force?

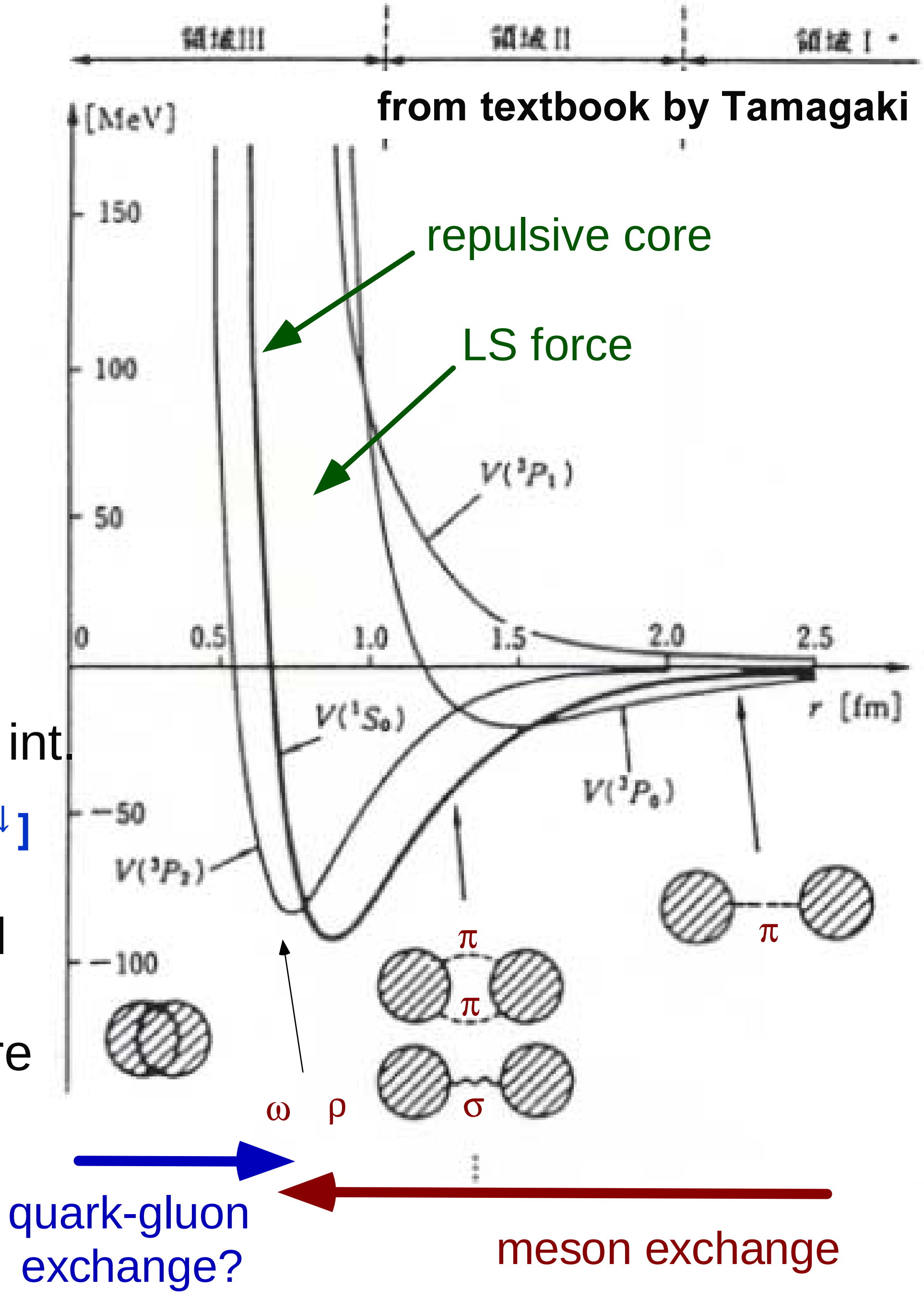
Short-range forces (=repulsive core, LS force) determine the "basic properties of nucleus" (=saturation, magic number).

Quark Cluster Model

- NN repulsive core
  Δ-N mass difference → color magnetic int.

  H dibaryon $[u^{\uparrow}u^{\downarrow}d^{\uparrow}d^{\downarrow}s^{\uparrow}s^{\downarrow}]$ **($SU_f(3) \times SU_f(3)$ singlet)**
  = Attractive core in $\Lambda\Lambda$-ΞN channel

- ΣN (I=3/2,S=1) strongly repulsive core
  ← quark Pauli
- LS force → quark gluon exchange
  → Λ : very small
  Σ : as large as N



Λ spin-orbit splitting in $^{13}_{\Lambda}C$

^{13}C (K^-, π^- γ)
BNL E929
w/ NaI array

$p_{1/2}$, $p_{3/2}$ single-particle level splitting

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

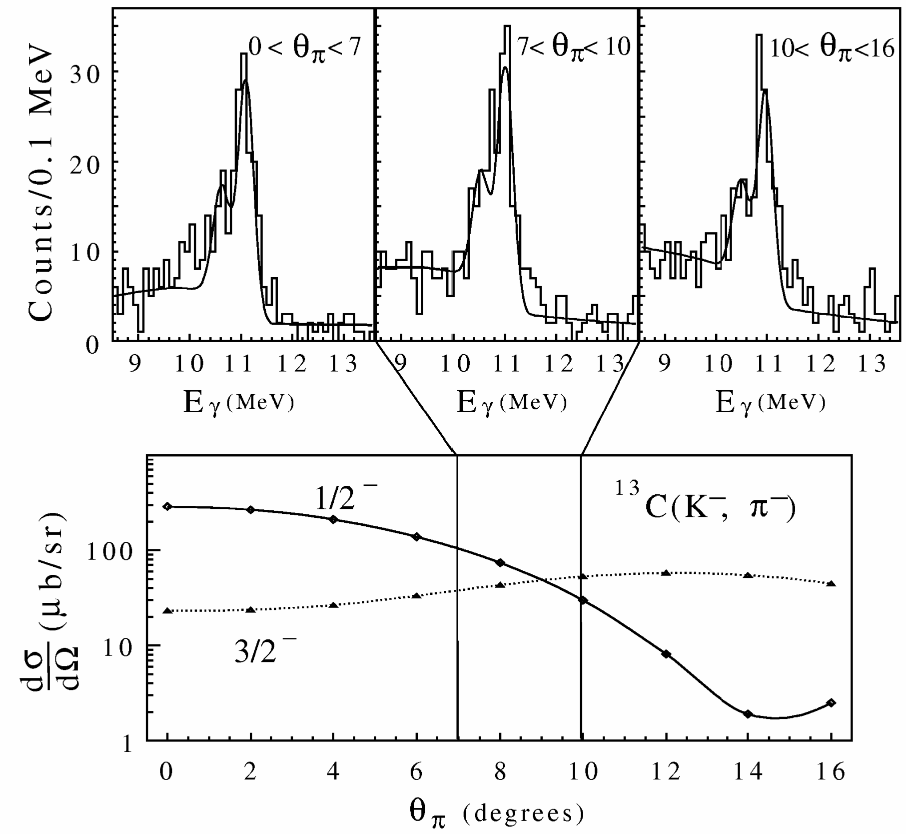
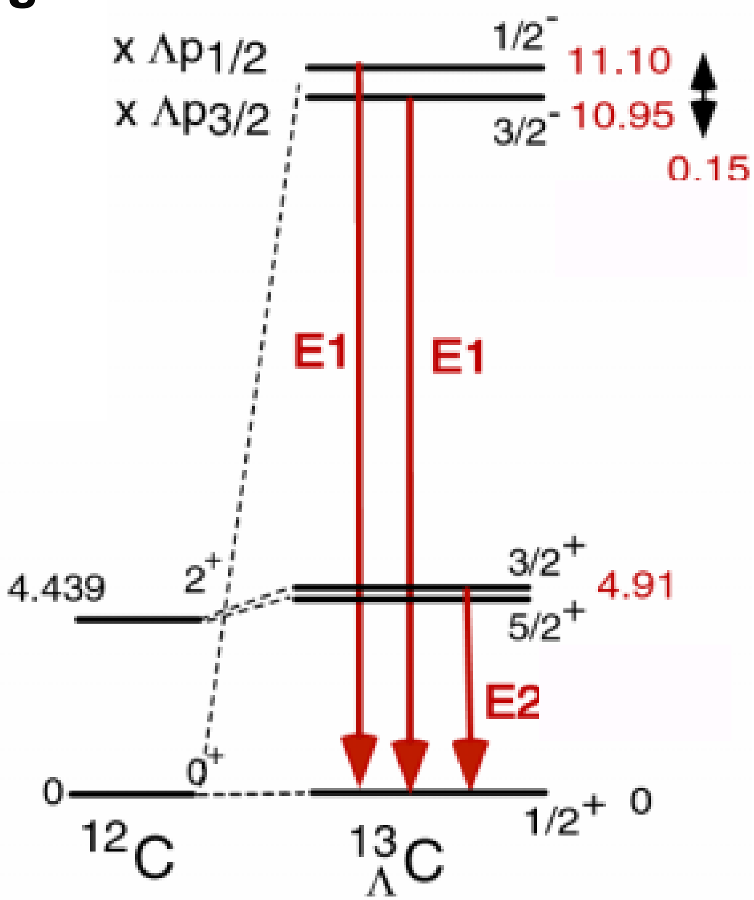
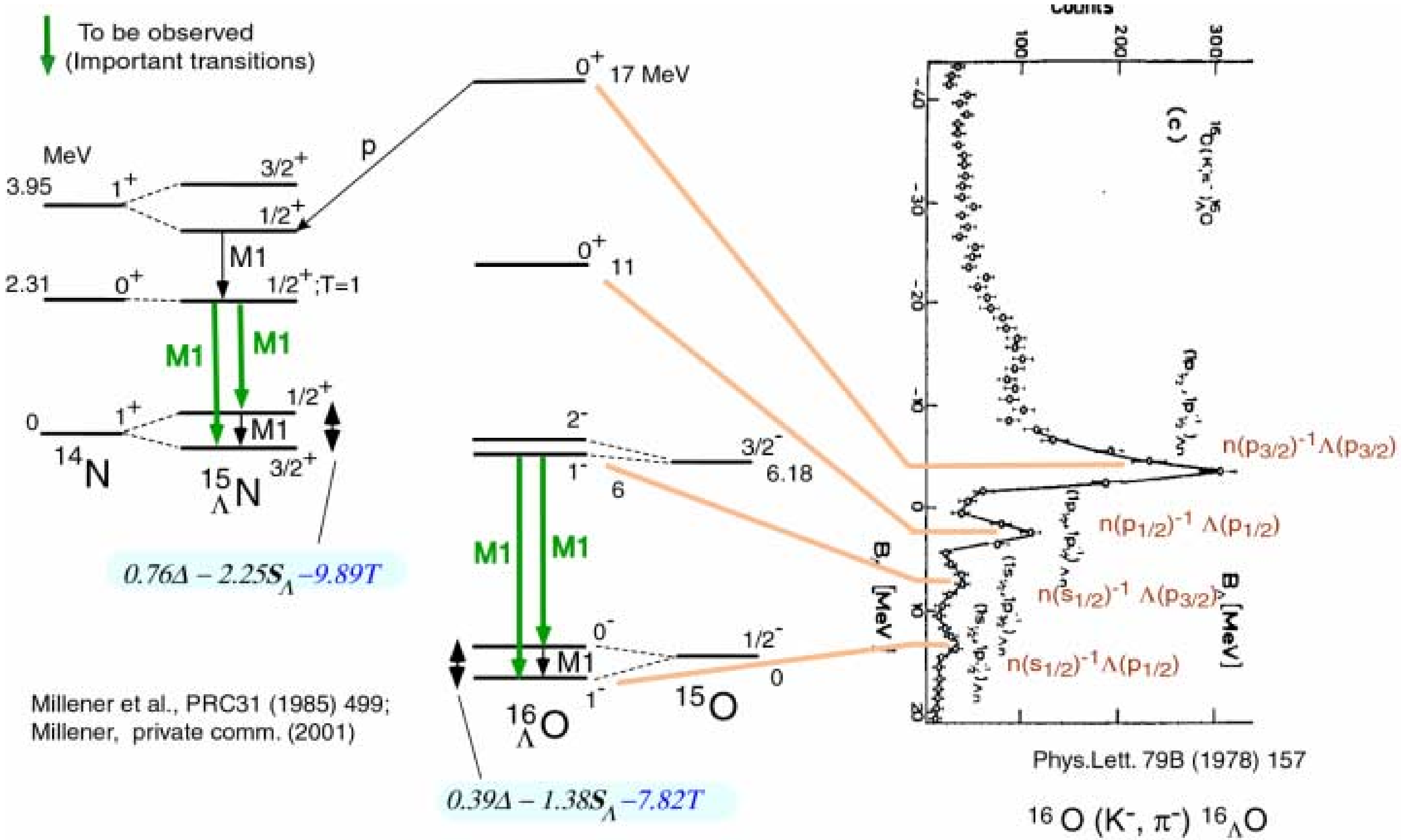


FIG. 2. γ ray spectra taken in coincidence with scattered π^-'s (upper panel) and differential cross section of $1/2^-$ and $3/2^-$ states calculated by Motoba [18] (lower panel) are shown.



Ajimura et al., PRL 86 (2001) 4255

How to measure Tensor term: $^{16}{}_{\Lambda}$O and $^{15}{}_{\Lambda}$N

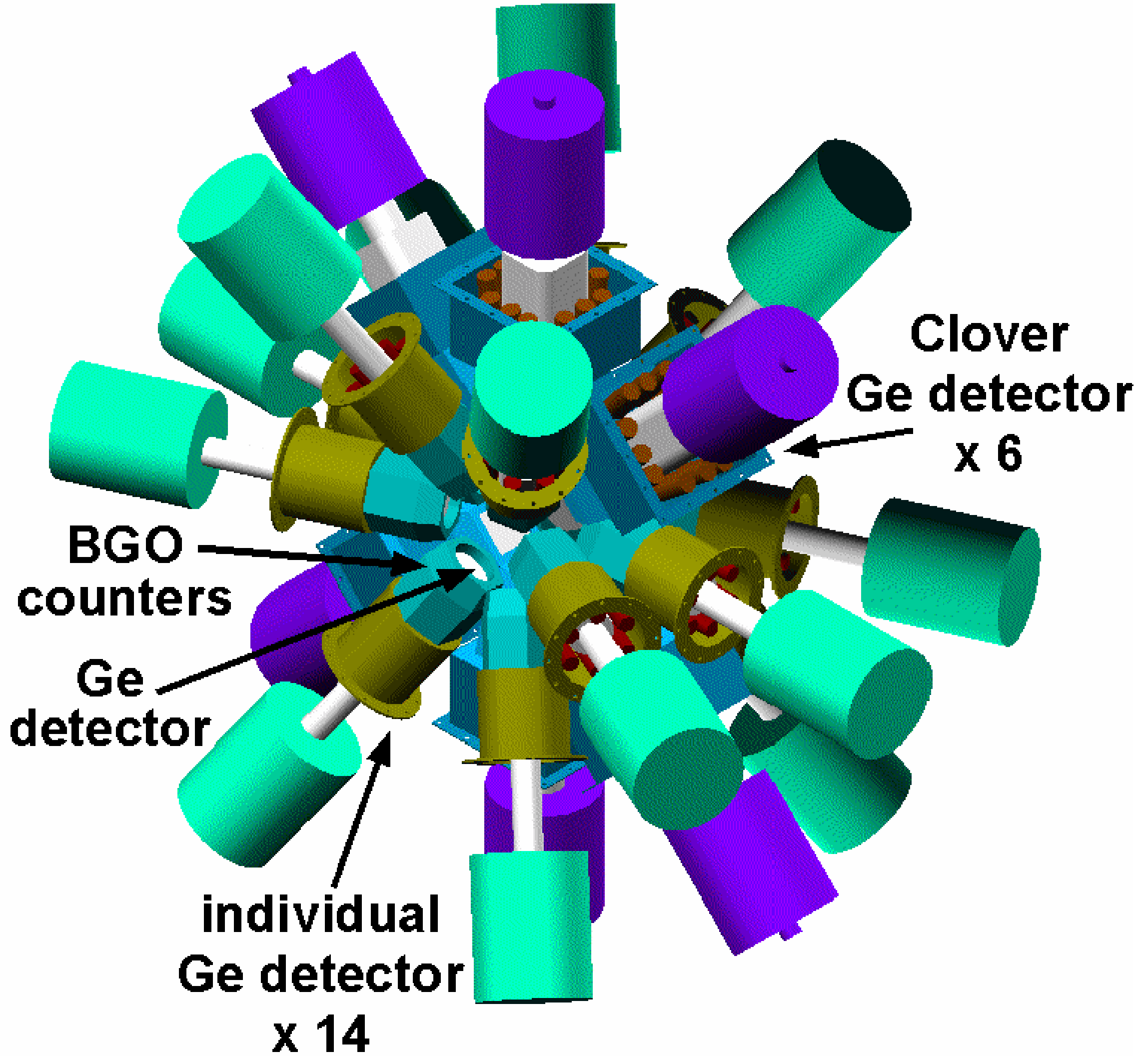


p1/2 shell --- Large contribution of the tensor term

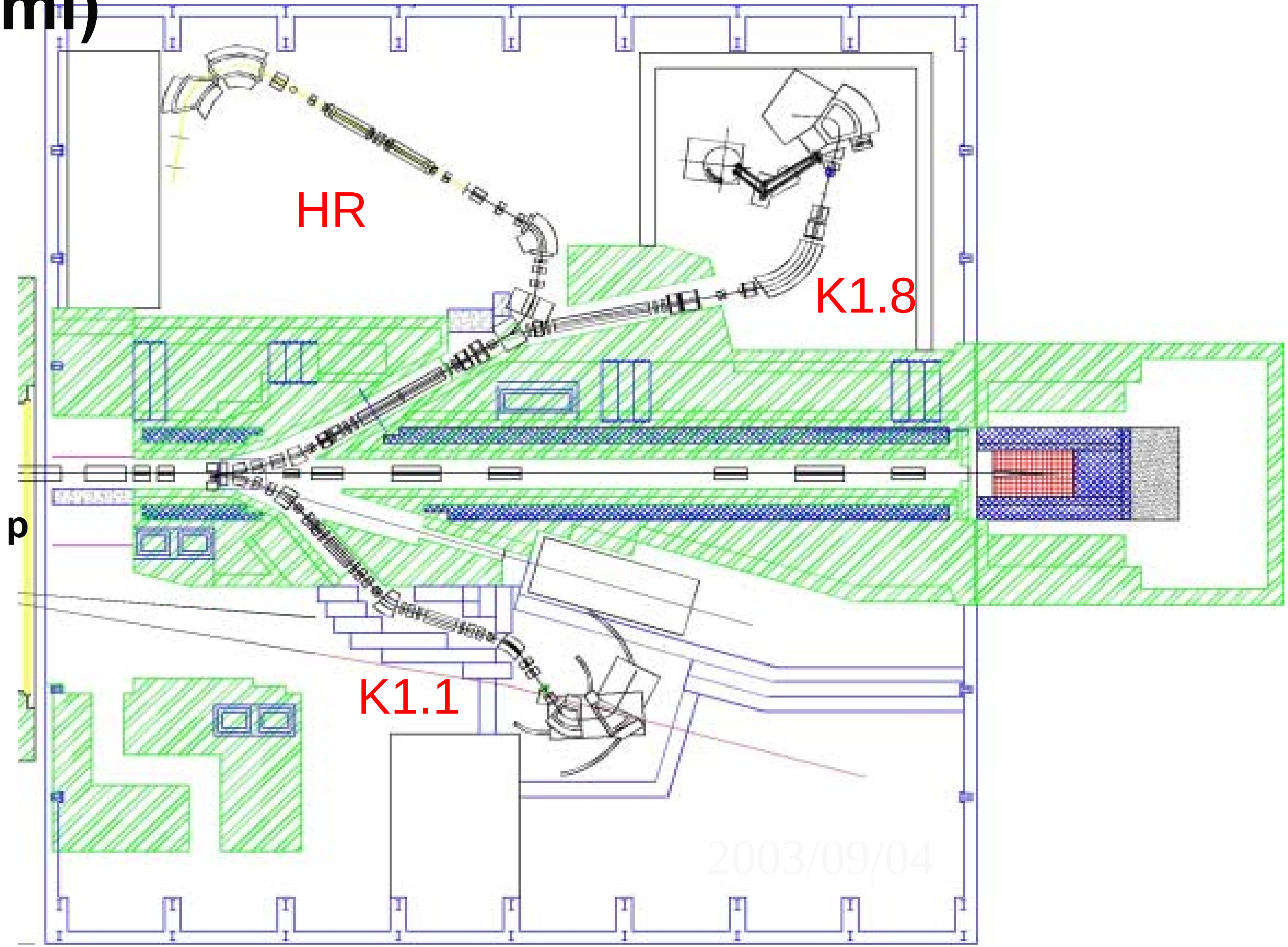
Upgrade of Hyperball

Construction of Hyperball2 in progress. Ready in 2004

- Clover Ge (r.e. >120%)
  +BGO x 6 added
- Peak eff.
  ~ 2.5% -> 5% at 1 MeV
- Beam test of Clover Ge
  (T536, June 2003) OK
- VME-based fast readout
- Improvement of preamplifie

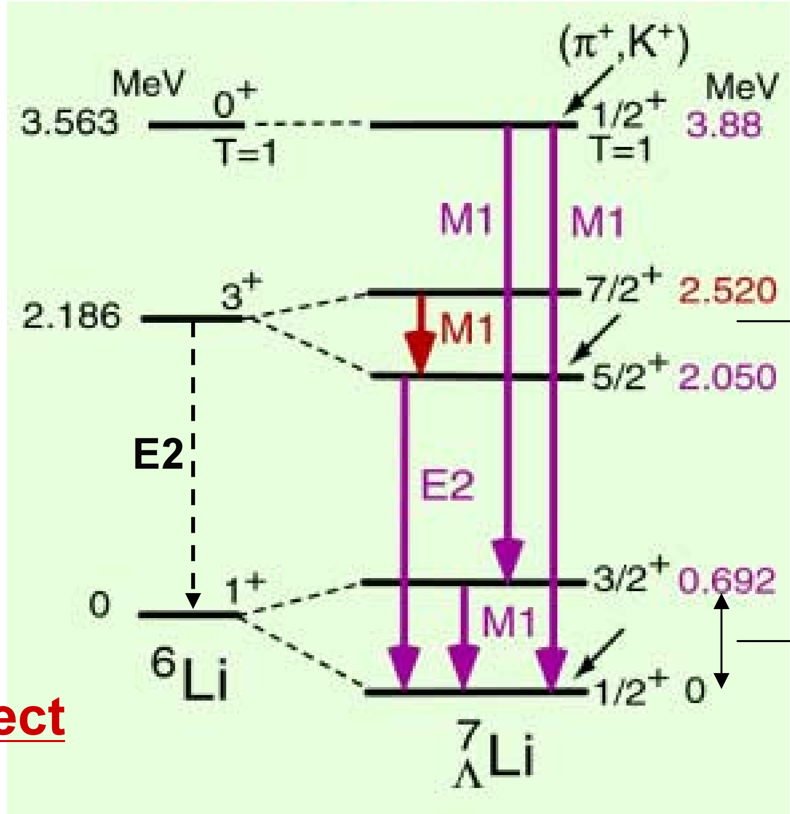


J-PARC NP-Hall (a sample plan by Noumi)



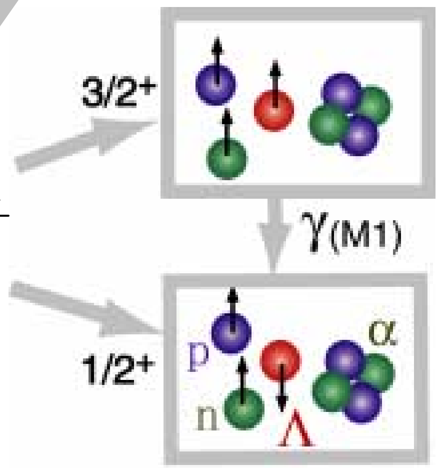
50 GeV p

Physics output from $^{7}_{\Lambda}$Li



N- LS interaction

S_N~ -0.4 MeV



spin-spin interaction

Δ = 0.50 MeV

shrinking effect

Predicted by
Motoba et al.,
Prog.Theor.Phys.
70 (1983) 189.

B(E2)
$\propto$ | <f | e r^2 Y$_2$ | i > |^2
$\propto$ R^4