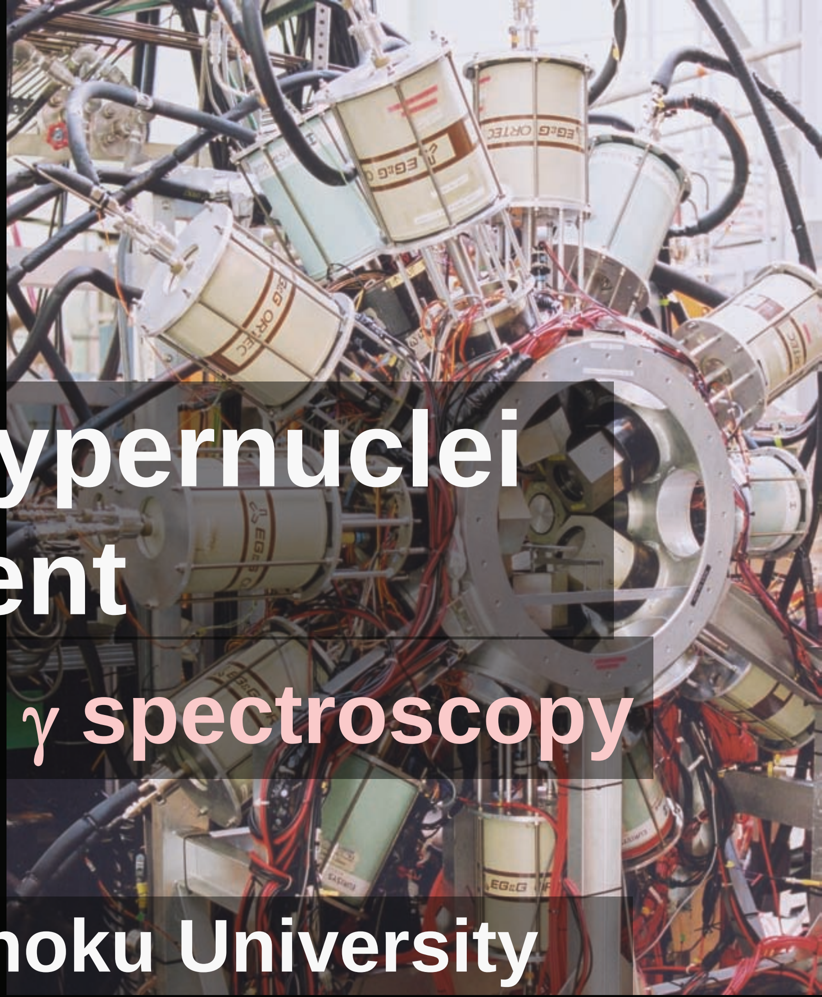
Λ

Spectroscopy of hypernuclei -- experiment

Mainly on γ spectroscopy



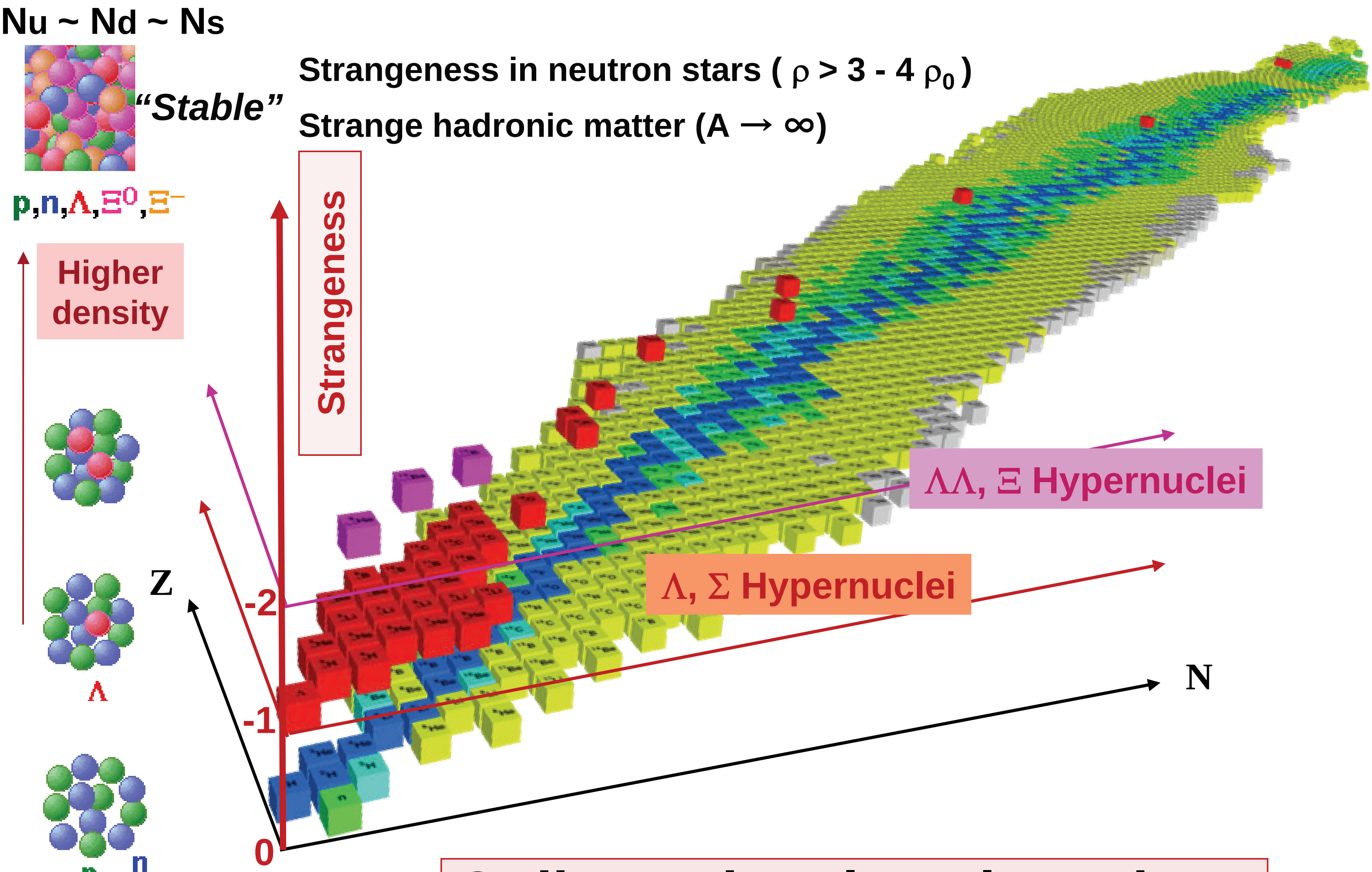
Dept. of Physics, Tohoku University
H. Tamura

Reference
O. Hashimoto and H. Tamura,
Progress of Particle and Nuclear Physics 57 (2006) 564.

Contents

1. Introduction for hypernuclear physics

World of matter made of u, d, s quarks



3-dimensional nuclear chart

by M. Kaneta inspired by HYP06 conference poster

Hyperon mixing in neutron star core

Large neutron Fermi energy -> Hyperons appear

Baryon fraction: very sensitive to YN, YY interactions

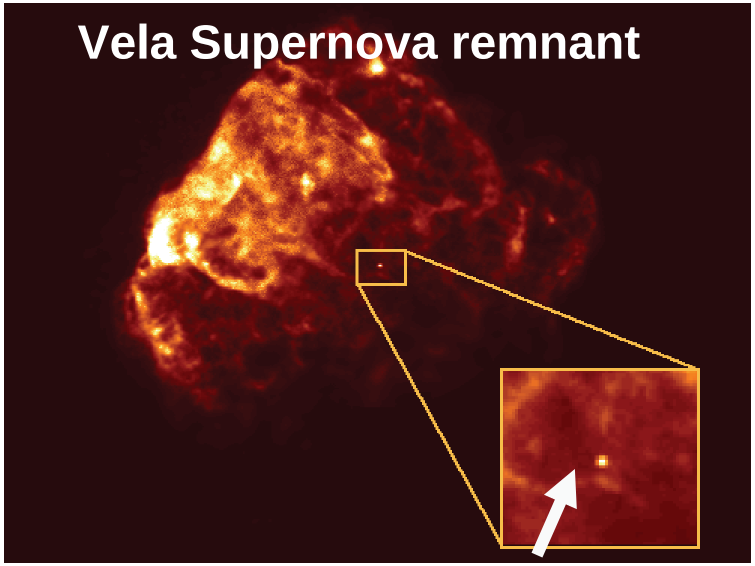
-> Affect maximum mass, cooling speed

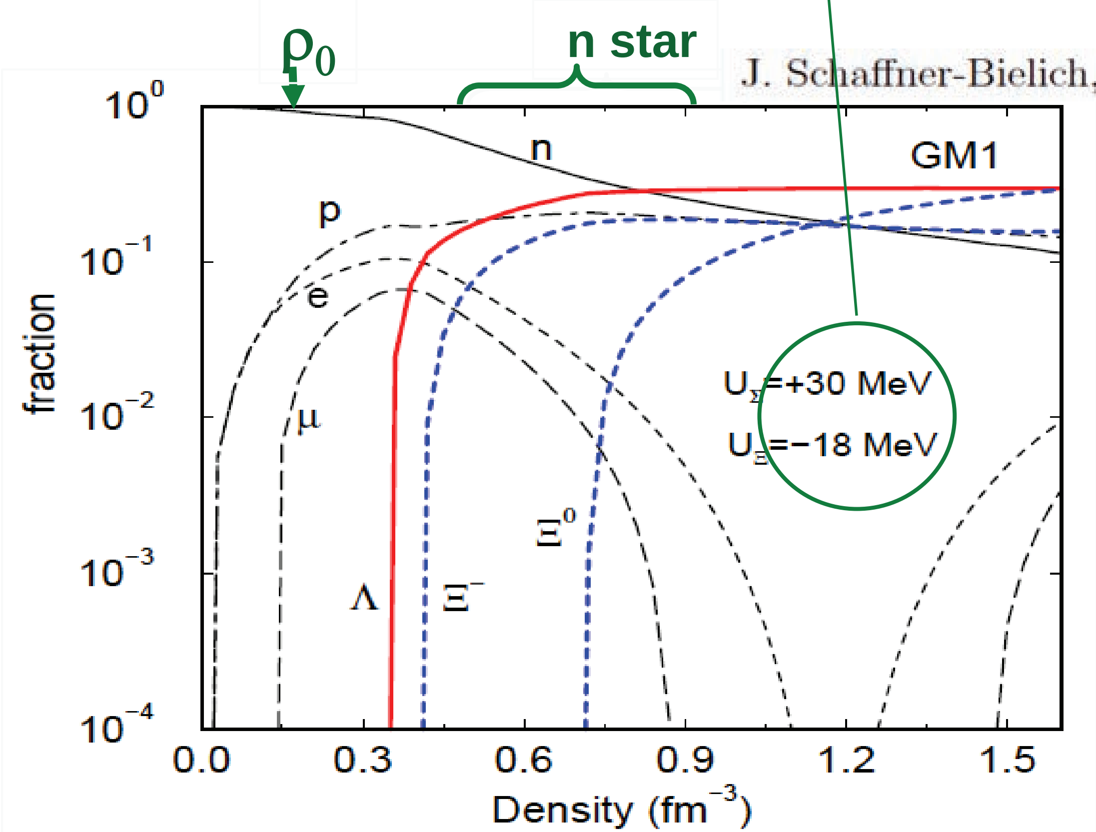
YN scattering experiments are extremely difficult.

Hypernuclear data -> realistic calculations become possible

We still need ΞN int., ΛΛ int., ΣN int., $\bar{K}$N int.,
ΛN-ΣN force, ΛN p-wave force,
NNN and YNN force, …

One probable assumption but should be determined by exp.





Do we understand the nuclear force?

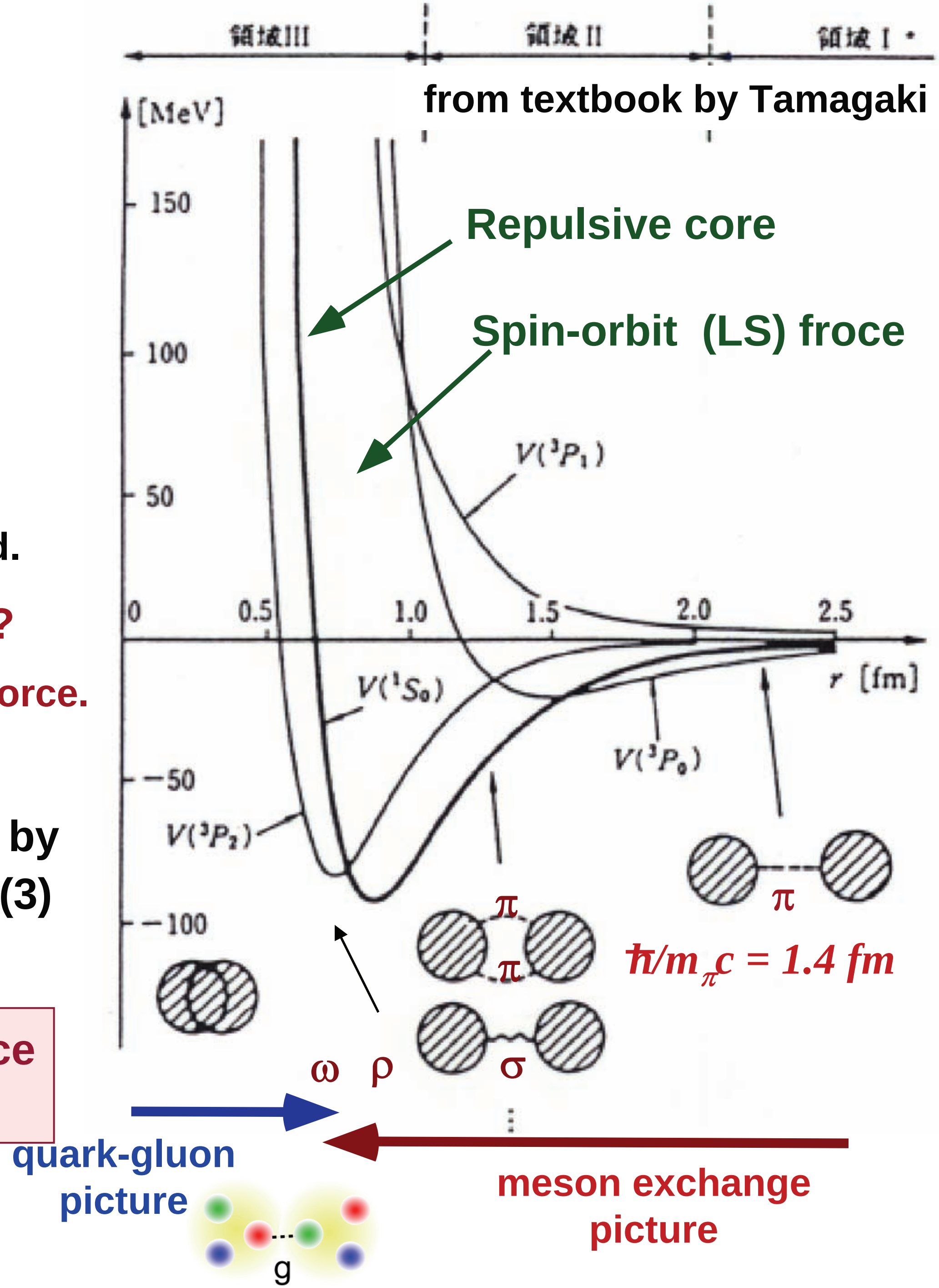
Short-range parts
（Repulsive core, Spin-orbit force）
ー Cause elementary properties of nucleus（saturation, magic numbers)
ー Origins are not understood. Meson exchange model seems invalid.

→ Quark-gluon picture necessary ?

s quark may change the quark gluon force.

Baryon-baryon force including strangeness can be also described by meson exchange picture under $SU_f(3)$ symmetry ?

Extending nuclear force to B-B force will answer these questions.

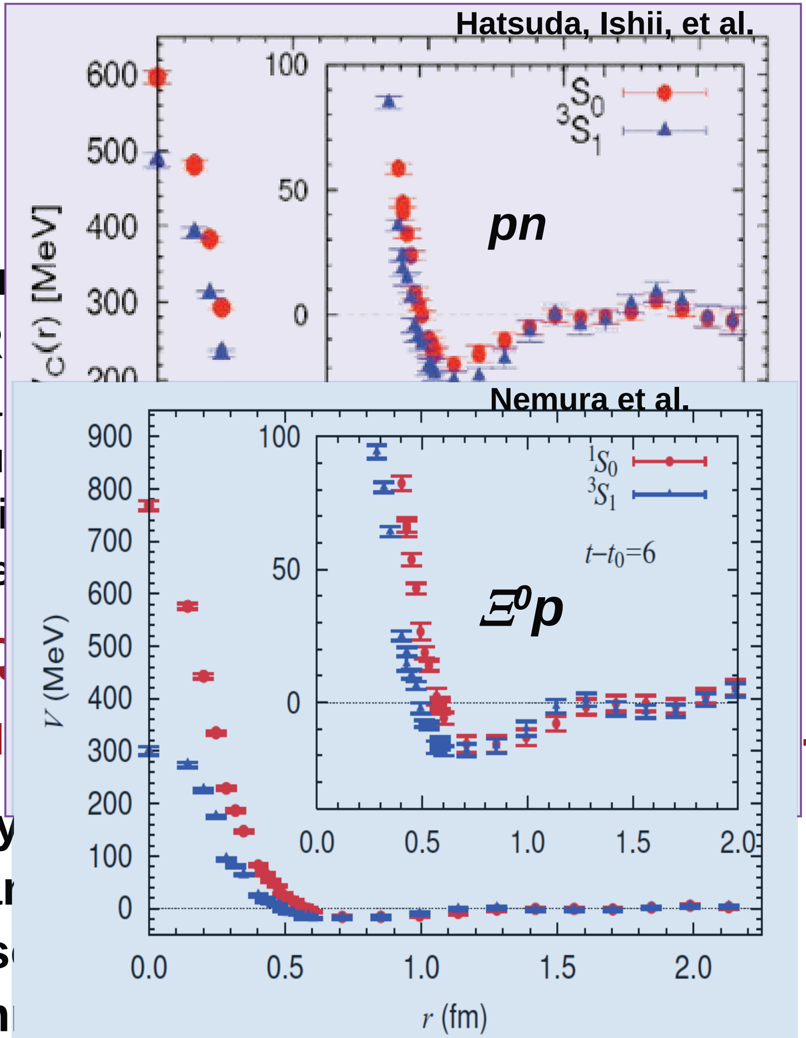


Shor
(R
—Ca
nu
—Ori
Me

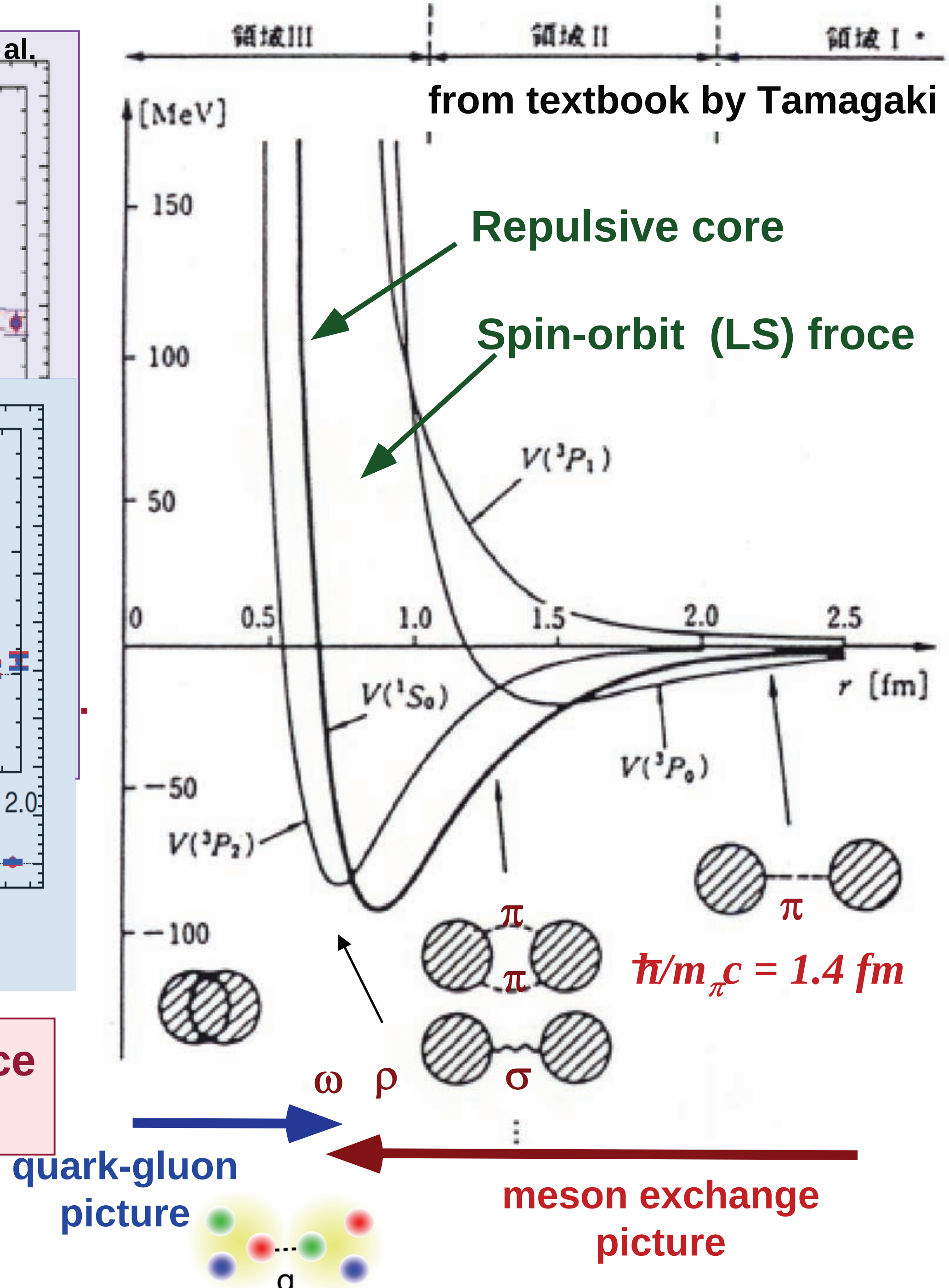
→ Q

s q

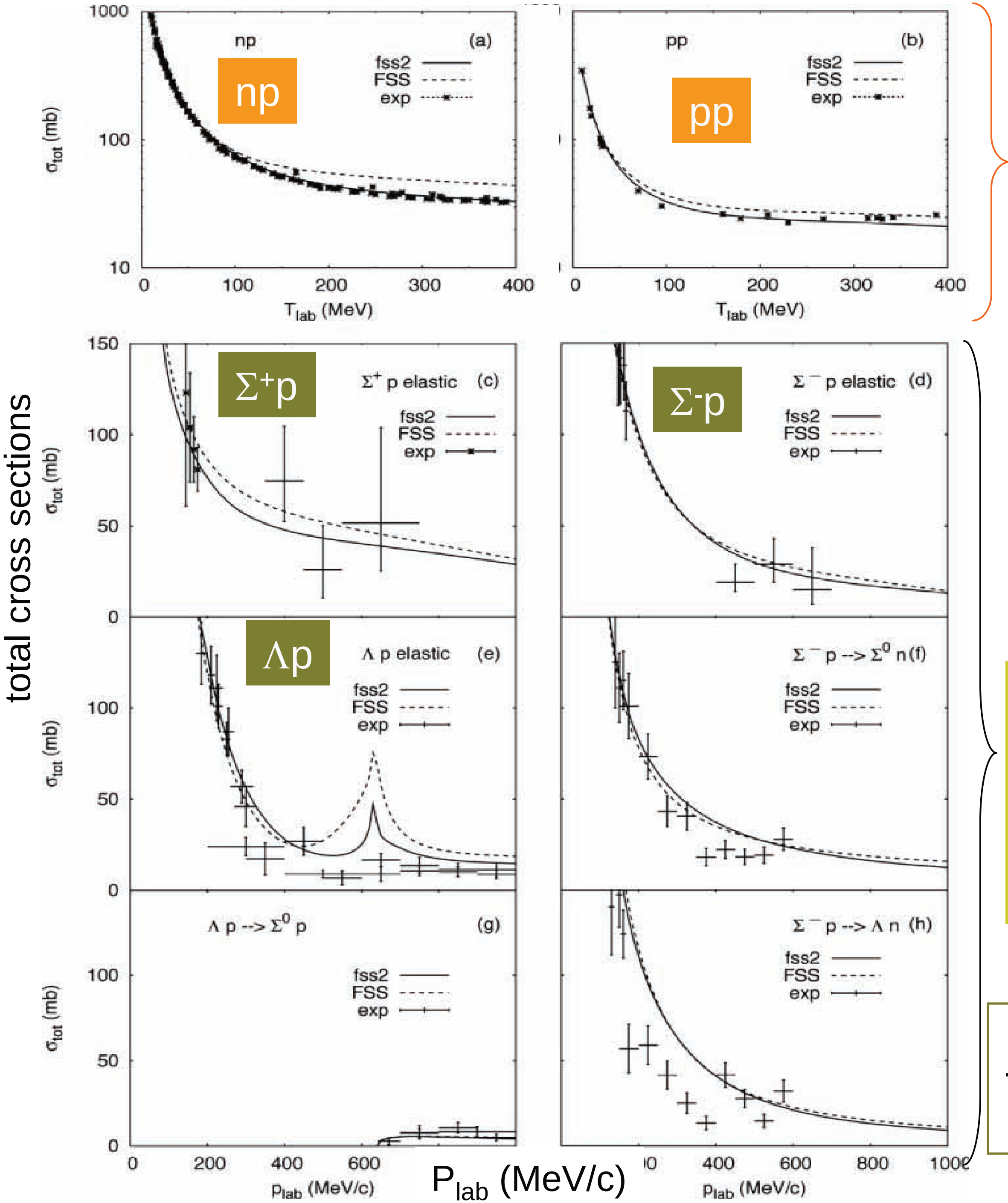
Bary
strar
mes
sym



Extending nuclear force to B-B force will answer these questions.



Limited YN scattering data



NN forces
Experimentally determined very well
by pp and pn scattering exp.
in wide momentum range
with spin observables
-> phase shift analysis

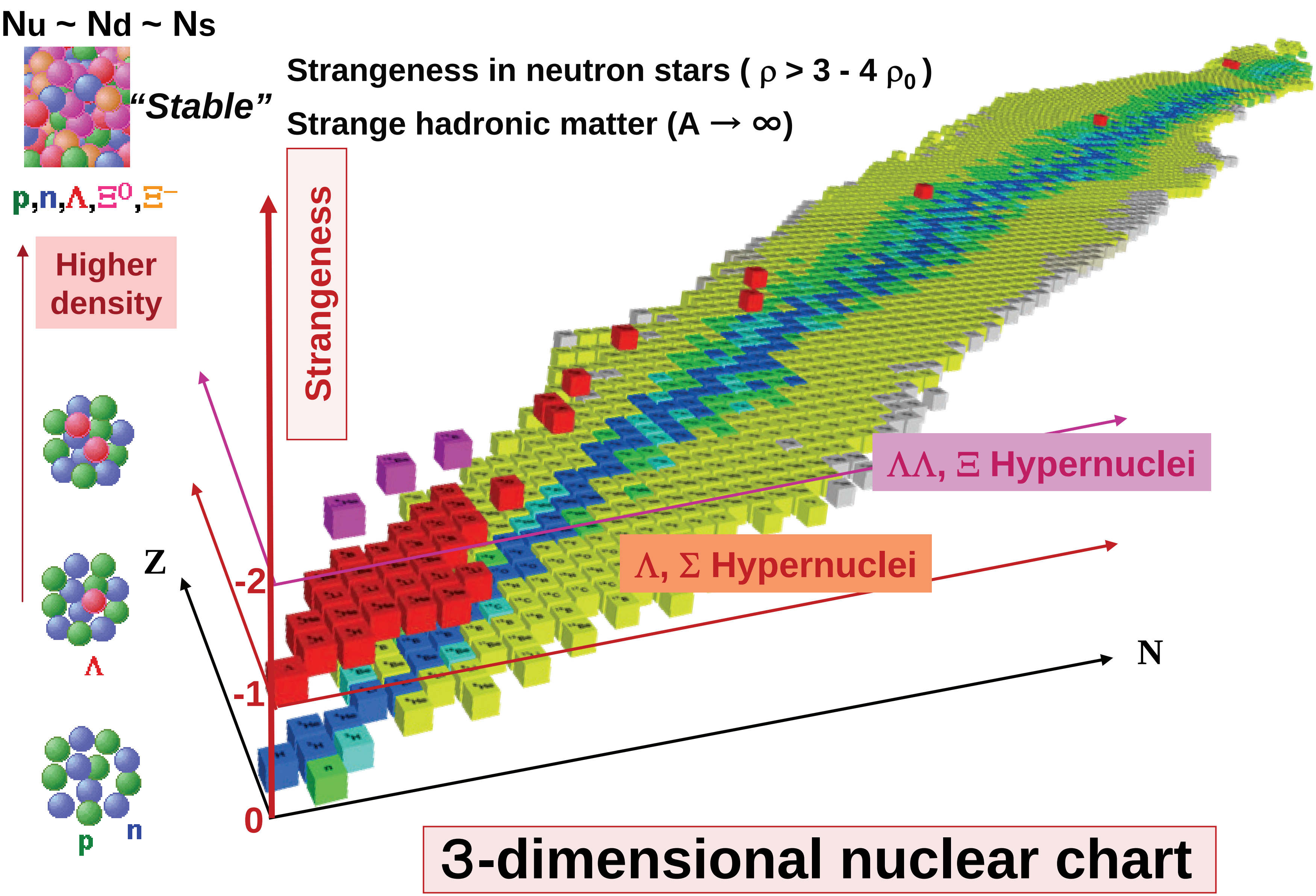
YN forces
Statistically poor
Limited momentum region

$c\tau(\Lambda) = 7.9$ cm, $c\tau(\Sigma^{+}) = 2.4$ cm

information of YN (and YY) forces from hypernuclear structure
-> <u>Spectroscopic data necessary</u>

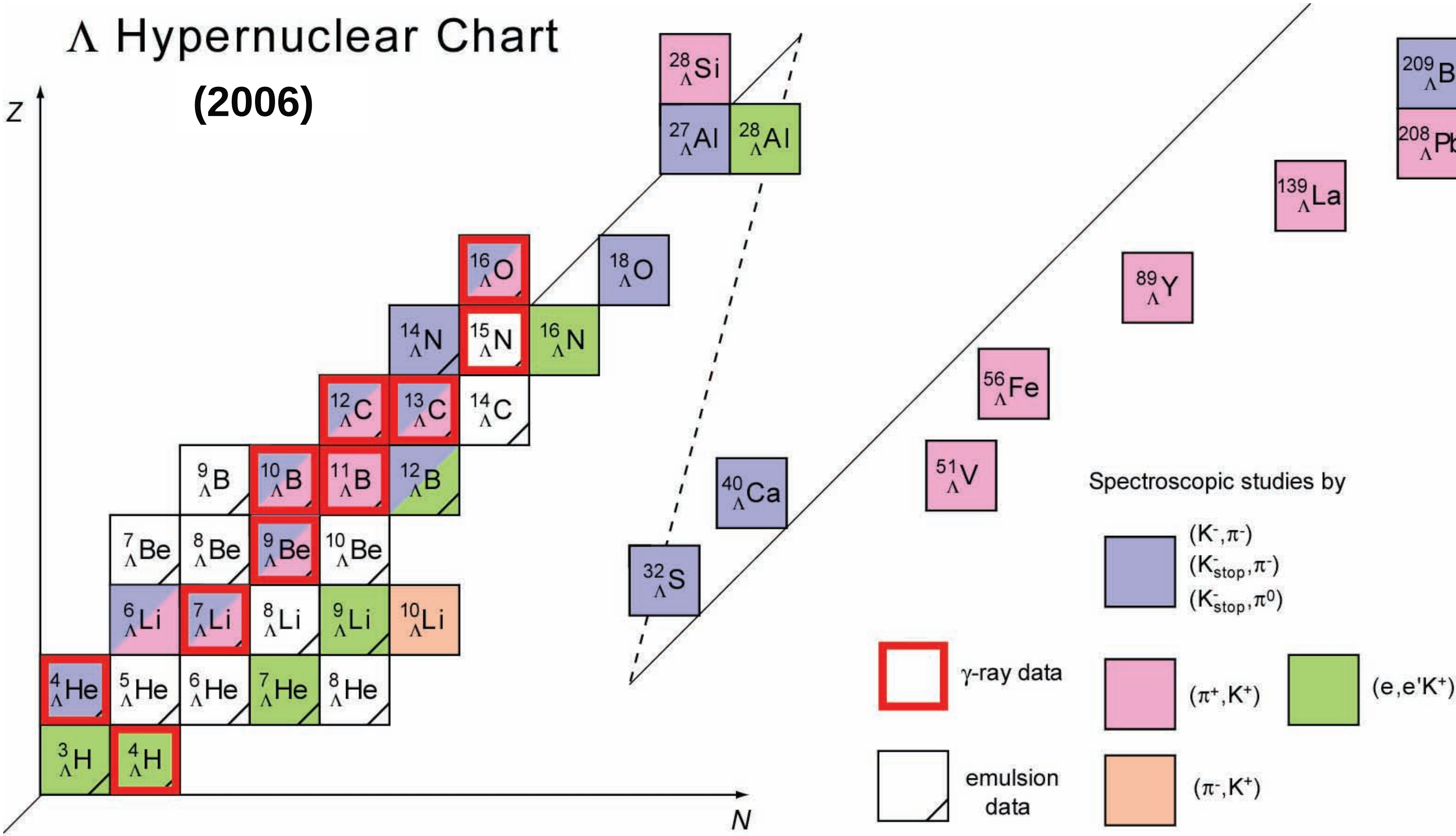
2. Brief Summary of Reaction Spectroscopy

World of matter made of u, d, s quarks



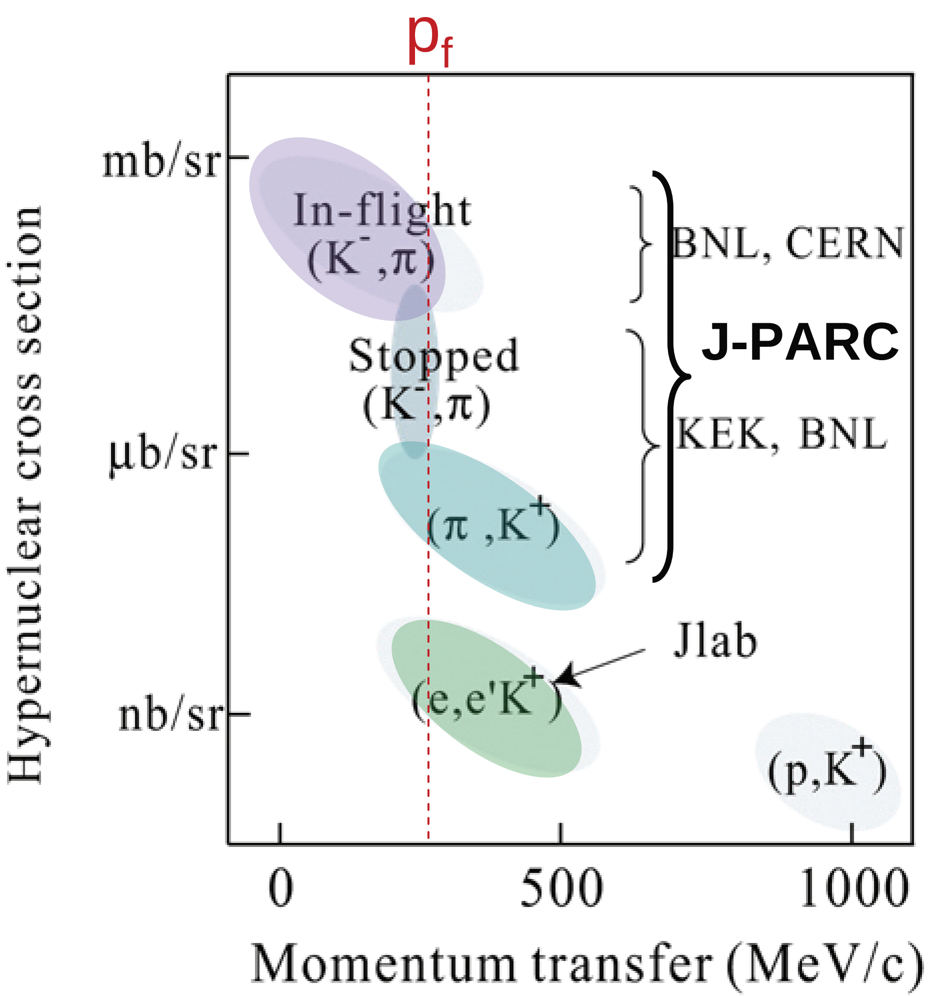
by M. Kaneta inspired by HYP06 conference poster

Present Status of Λ Hypernuclear Spectroscopy



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

Characteristics of hypernuclear production reactions



Beam intensity

K^- : 10^4-10^5/s @KEK-PS

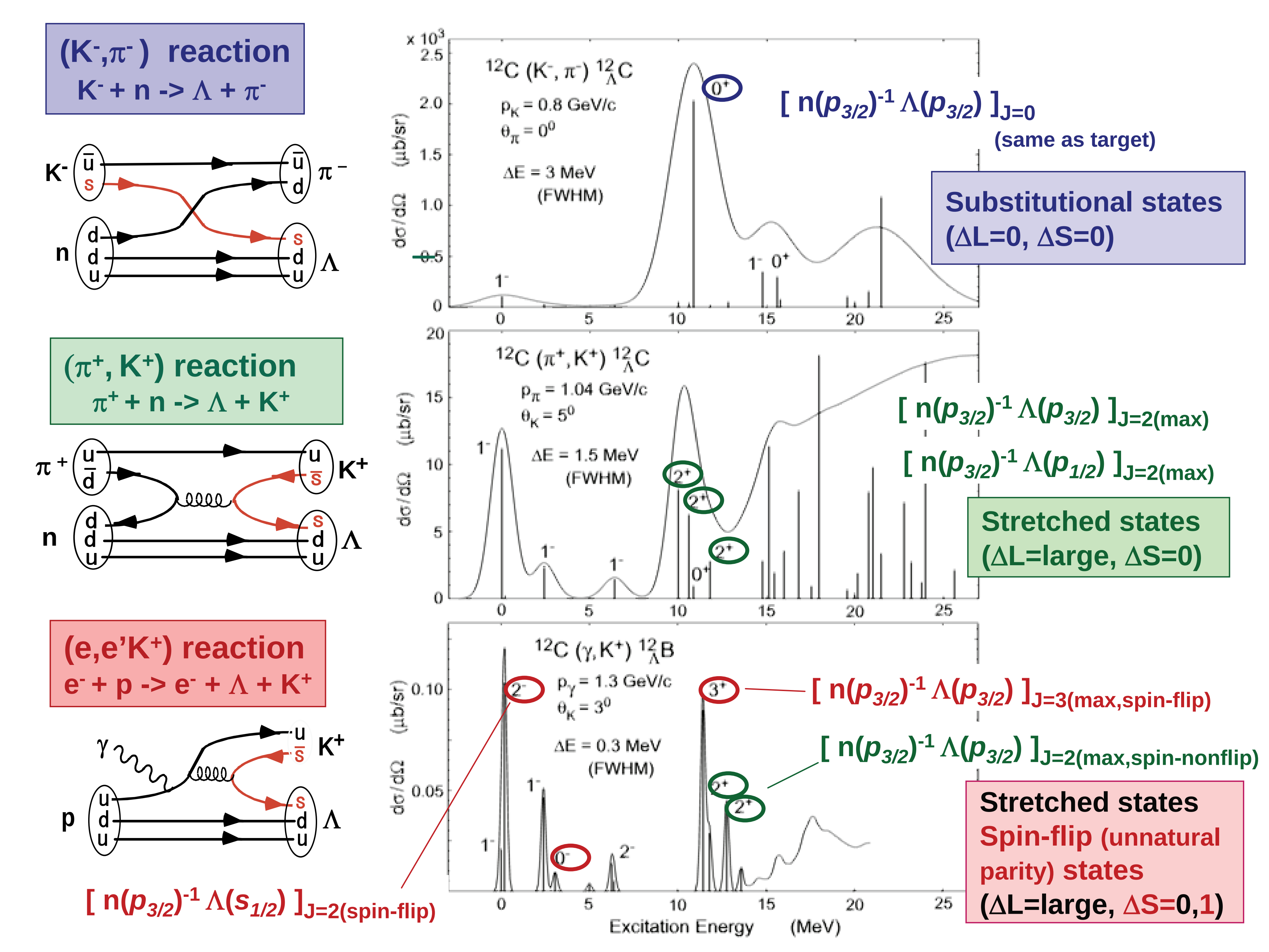
~10^6/s @BNL-AGS

~10^7/s @J-PARC

π^+ : 3×10^6/s @KEK-PS

10^9/s @ J-PARC

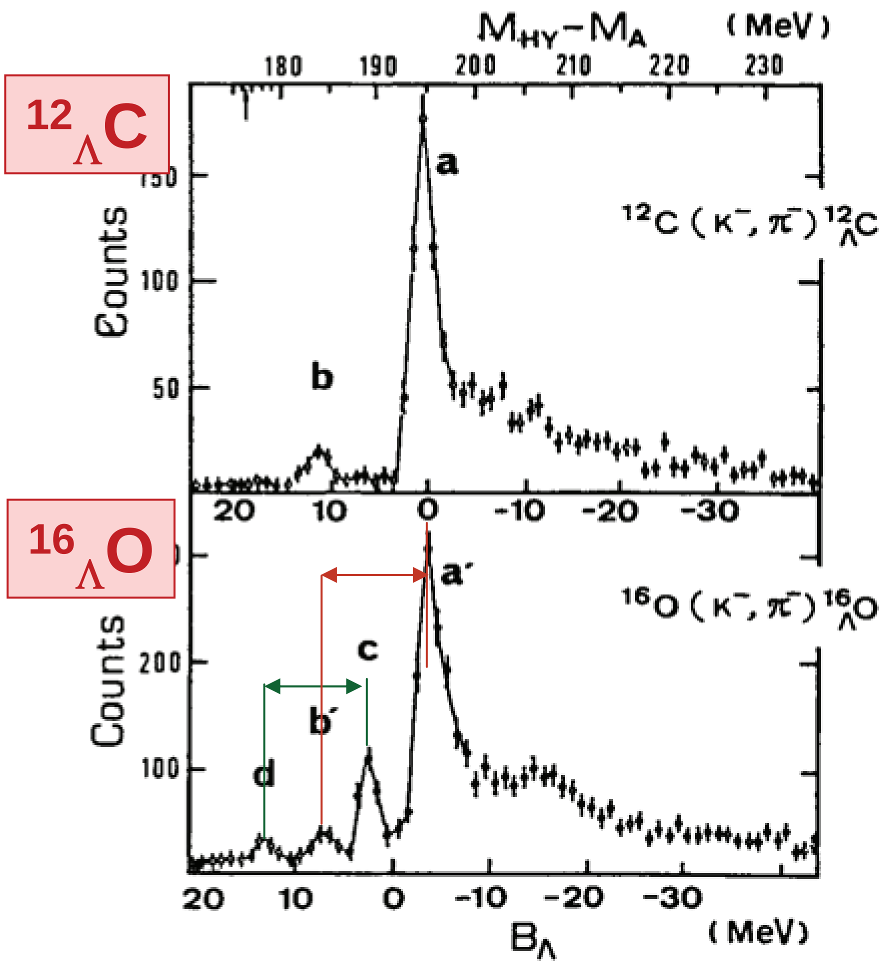
e : ~ 5×10^{14}/s_Jlab-CEBAF



(K⁻,π⁻) reaction
K⁻ + n -> Λ + π⁻
(π⁺, K⁺) reaction
π⁺ + n -> Λ + K⁺
(e,e'K⁺) reaction
e⁻ + p -> e⁻ + Λ + K⁺
¹²C (K⁻, π⁻) ¹²ΛC
p_K = 0.8 GeV/c
θ_π = 0⁰
ΔE = 3 MeV (FWHM)
¹²C (π⁺,K⁺) ¹²ΛC
p_π = 1.04 GeV/c
θ_K = 5⁰
ΔE = 1.5 MeV (FWHM)
¹²C (γ,K⁺) ¹²ΛB
p_γ = 1.3 GeV/c
θ_K = 3⁰
ΔE = 0.3 MeV (FWHM)
dσ/dΩ (μb/sr)
Excitation Energy (MeV)
[n(p3/2)⁻¹ Λ(p3/2)]J=0
(same as target)
Substitutional states
(ΔL=0, ΔS=0)
[n(p3/2)⁻¹ Λ(p3/2)]J=2(max)
[n(p3/2)⁻¹ Λ(p1/2)]J=2(max)
Stretched states
(ΔL=large, ΔS=0)
[n(p3/2)⁻¹ Λ(p3/2)]J=3(max,spin-flip)
[n(p3/2)⁻¹ Λ(p3/2)]J=2(max,spin-nonflip)
[n(p3/2)⁻¹ Λ(s1/2)]J=2(spin-flip)
Stretched states
Spin-flip (unnatural parity) states
(ΔL=large, ΔS=0,1)

2.1 (K^-,π^-) and (π^+,K^+) spectroscopy

The best (K^-, π^-) data -- Very small Λ spin-orbit splitting



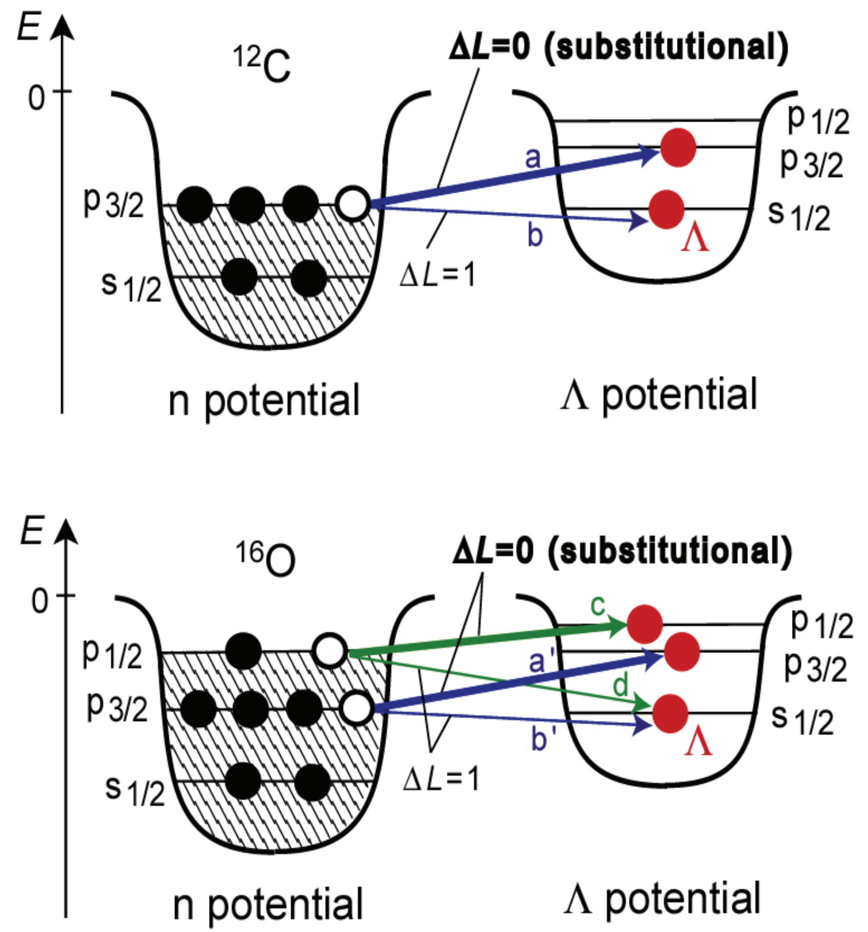


Fig. 4.2. Excitation spectra obtained from the (K^-, π^-) reaction on ^{12}C and ^{16}O at $p_K = 715$ MeV/c are plotted as a function of the transfer energy $M_{HY} - M_A$. The q-dependence (angular distribution) of the peak intensities is displayed in the right-half. (Taken from Ref. 59.)

Brueckner et al., PLB 79 (1978) 157

|[*E*a' - *E*b'] – [*E*c - *E*d] | < 0.5 MeV
~ | $E(\Lambda p_{1/2})$ - $E(\Lambda p_{3/2})$ |

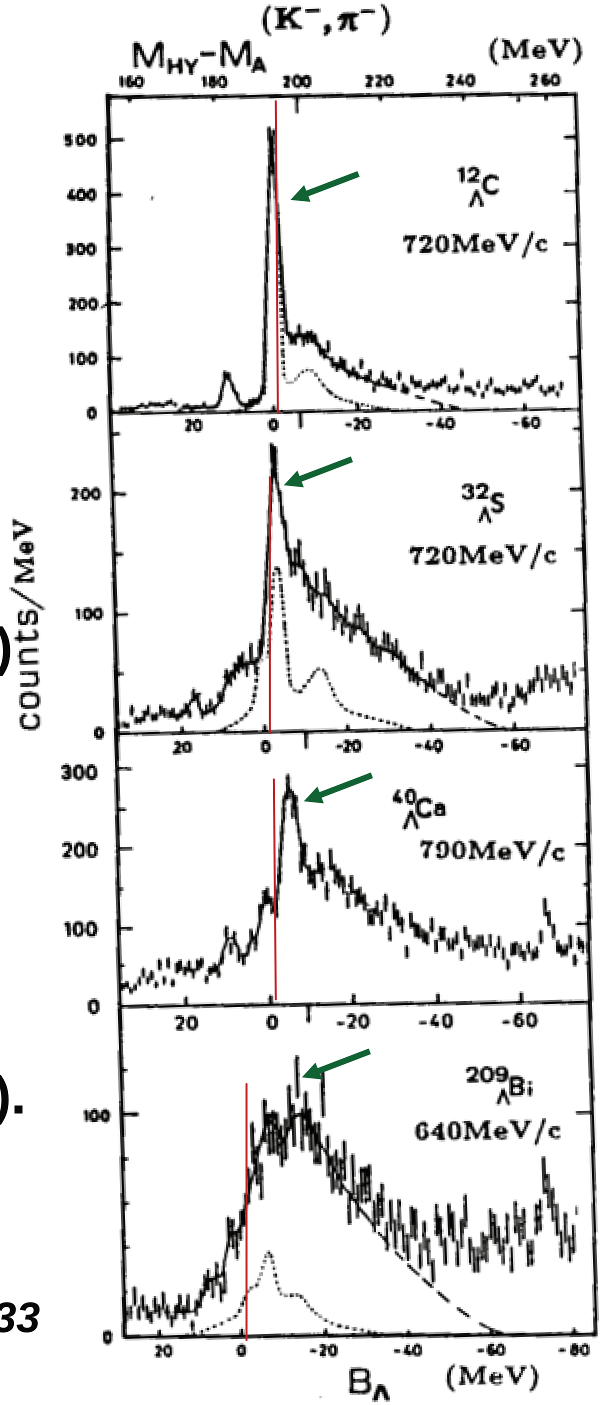
Limitation of (K$^-$, π^-) reaction

Small momentum transfer
< 50 MeV/c
-> Substitutional states only

Large A
-> n hole in outer shell (w/ large L)
-> Λ in the same outer shell
-> highly unbound
-> large widths
No information of deep Λ orbits

Population of deep Λ orbits requires a large ΔL (a large q > p_F).
=> (π^+,K$^+$) reaction

B. Povh, NPA 335 (1980) 233



n$(p_{3/2})^{-1}$ $\Lambda(p_{3/2})$

n$(d_{5/2})^{-1}$ $\Lambda(d_{5/2})$

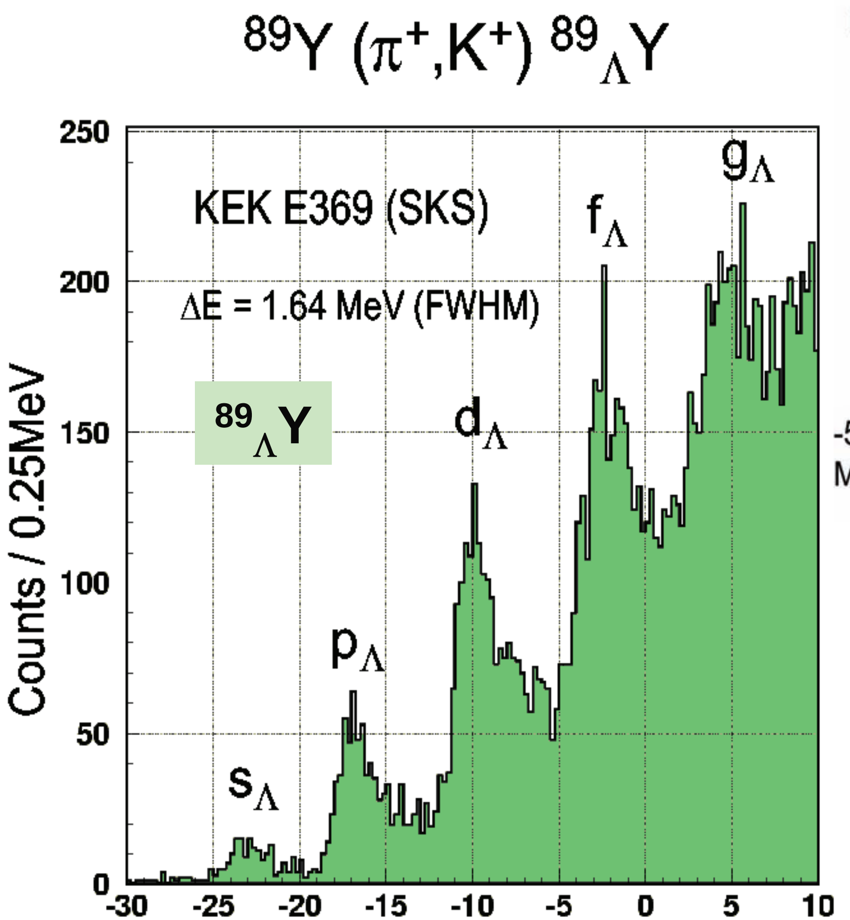
n$(d_{3/2})^{-1}$ $\Lambda(d_{3/2})$

n$(i_{13/2})^{-1}$ $\Lambda(i_{13/2})$

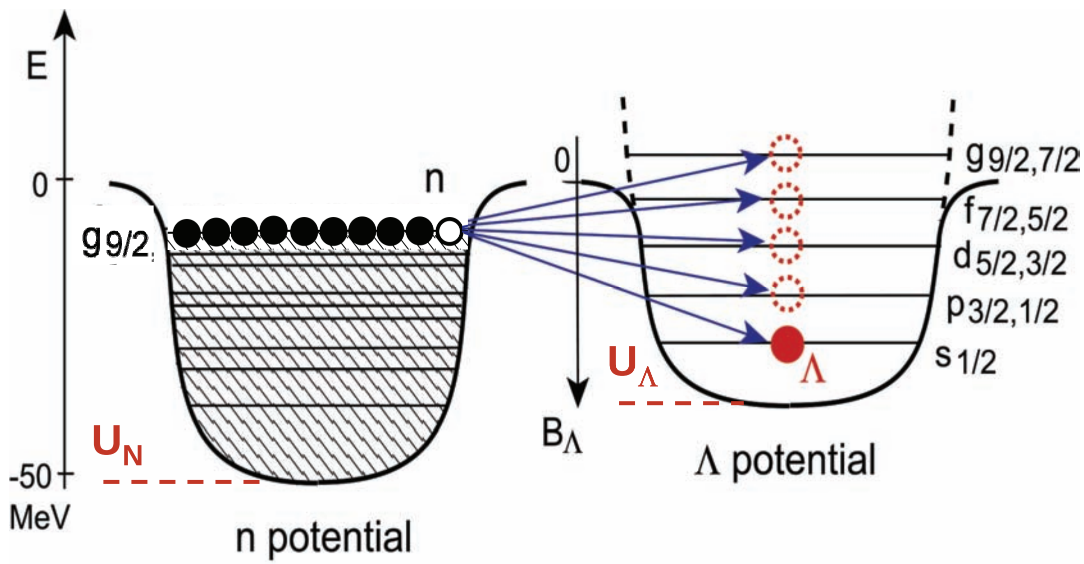
(π^+, K^+) spectroscopy

Large mom. transfer ~350 MeV/c -> Deeply bound states are well populated
-> large ΔL -> stretched states -> clear peaks

Hotchi et al., Phys.Rev.C 64 (2001) 044302

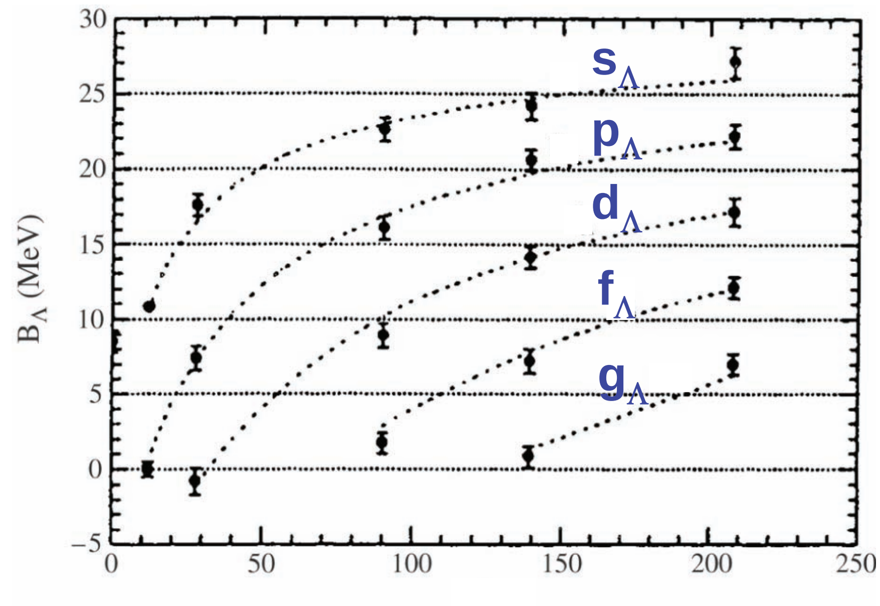


Mass of hypernucleus B_Λ (MeV)



- **Experimental direct evidence for single particle orbits deep in nucleus.**
  They cannot be seen by nucleons.
  Only hyperons (Λ) which are free from Pauli blocking make it possible.

Nuclear potential of Λ



-> Nuclear potential of Λ

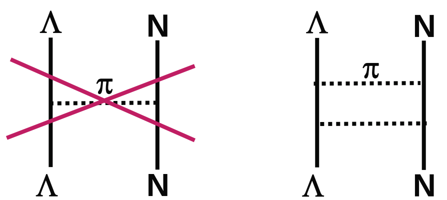
U_Λ = - 30 MeV (c.f. U_N = -50 MeV)

-> spin-averaged central force

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

Λ has no isospin -> one pion exchange forbidden

Long range force is missing



Better resolution is necessary

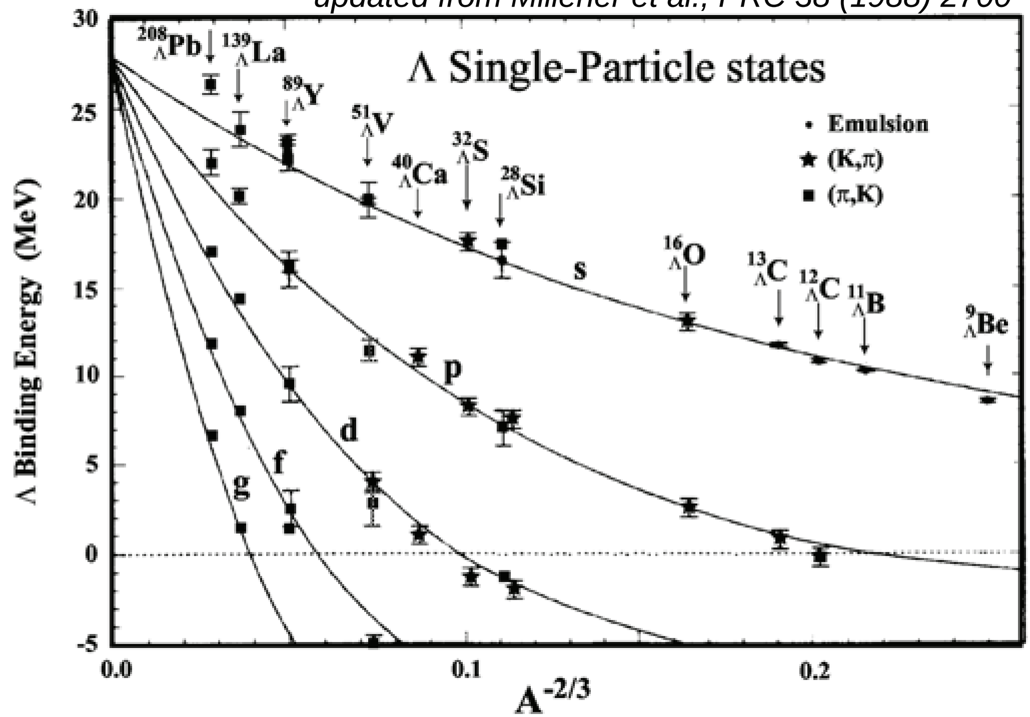
for ΛN spin-dependent forces,

ΛN-ΣN force, ..

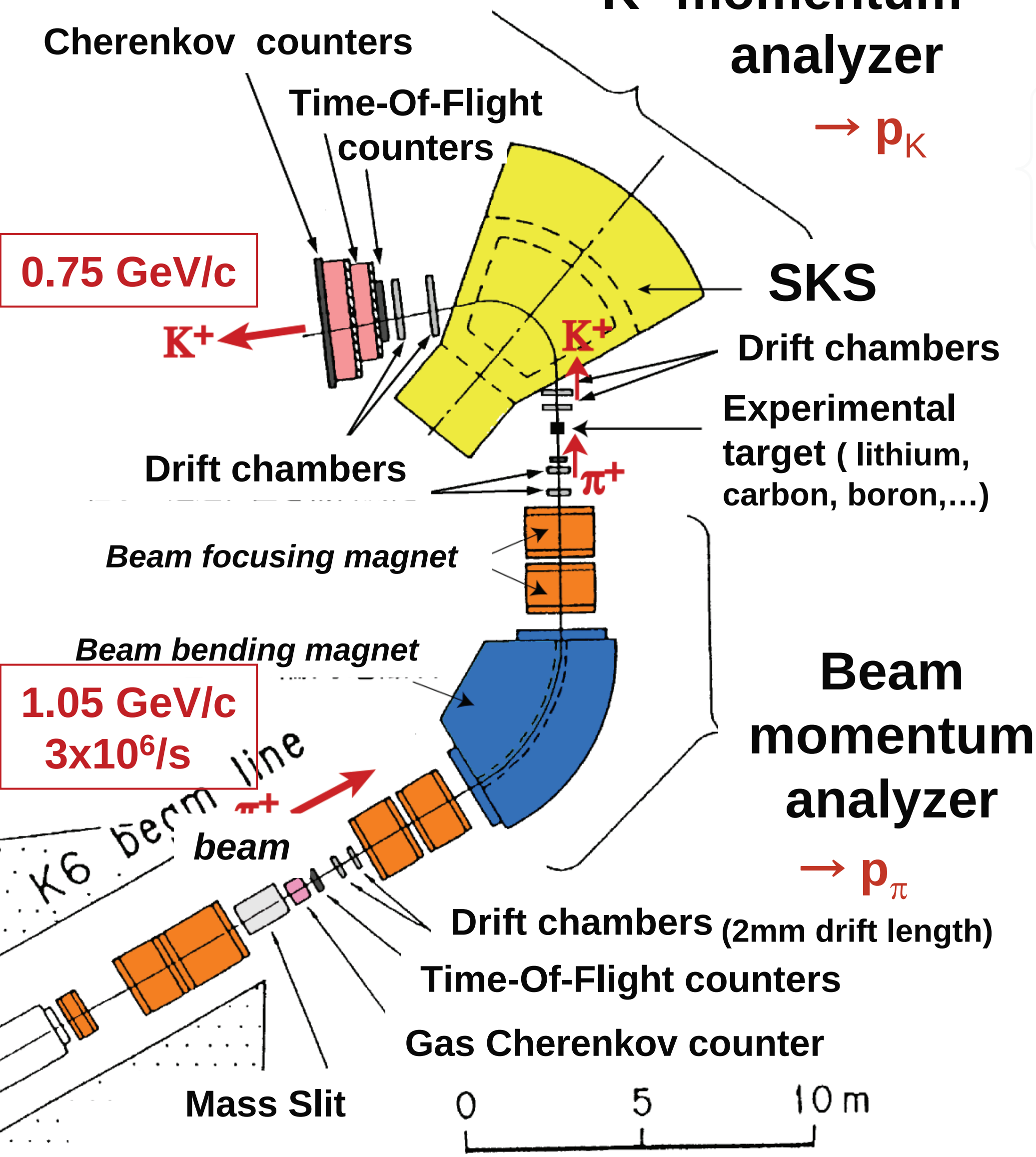
(π,K⁺) -> (e,e'K⁺) at JLab

γ spectroscopy

updated from Millener et al., PRC 38 (1988) 2700



Experimental apparatus -- case of (π^+, K^+)

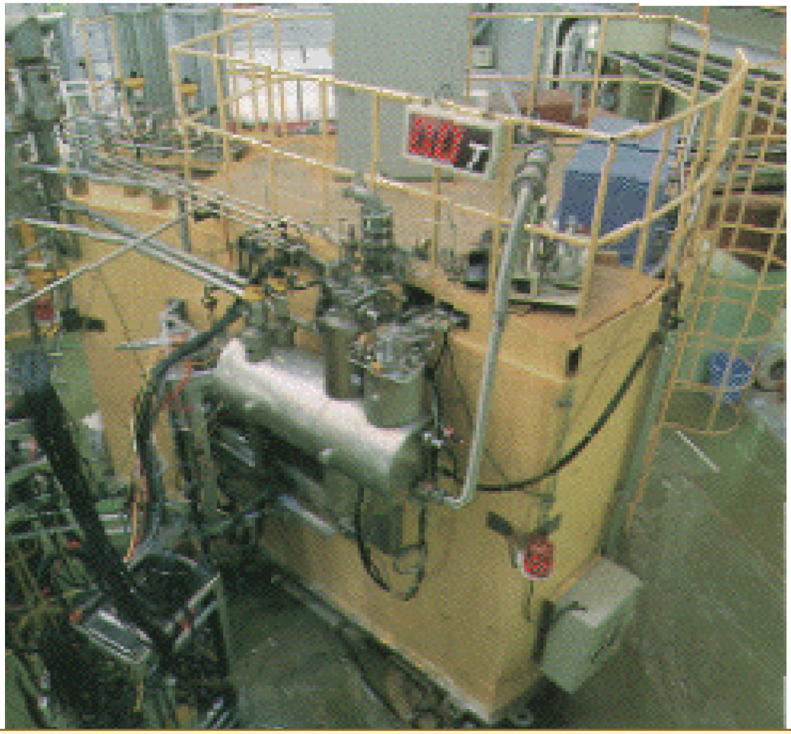


2-body reaction

$$\pi^+ + A(^AZ) \rightarrow Hy(^A{}_\Lambda Z) + K^+$$

$$p_\pi = p_{Hy} + p_K$$

$$\sqrt{p_\pi^2 + m_\pi^2} + m_A = \sqrt{p_{Hy}^2 + m_{Hy}^2} + \sqrt{p_K^2 + m_K^2}$$



SKS (3 T max)
(Superconducting Kaon Spectrometer)

Experimental apparatus -- case of (π^+,K^+)

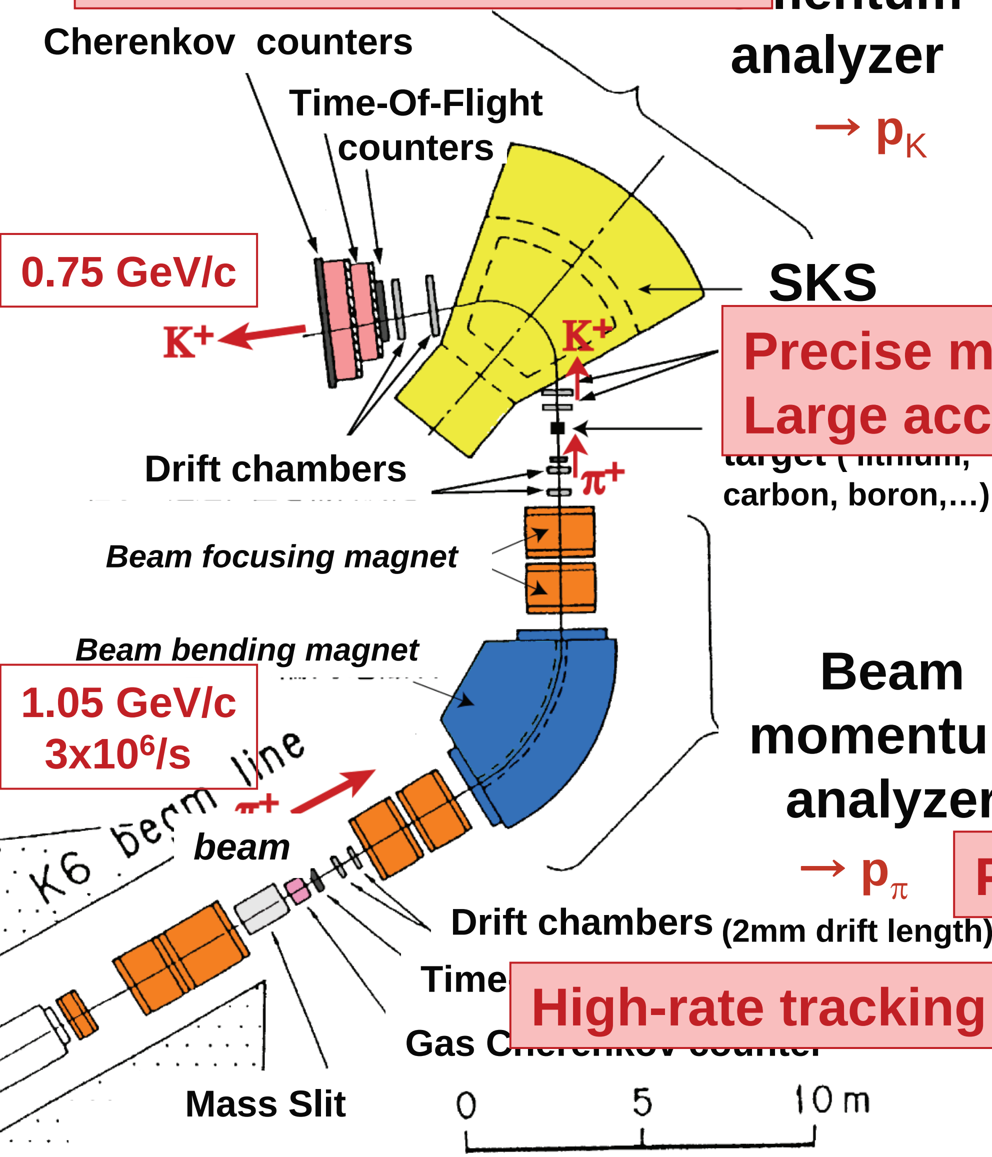
God particle identification
π / K / p

2-body reaction

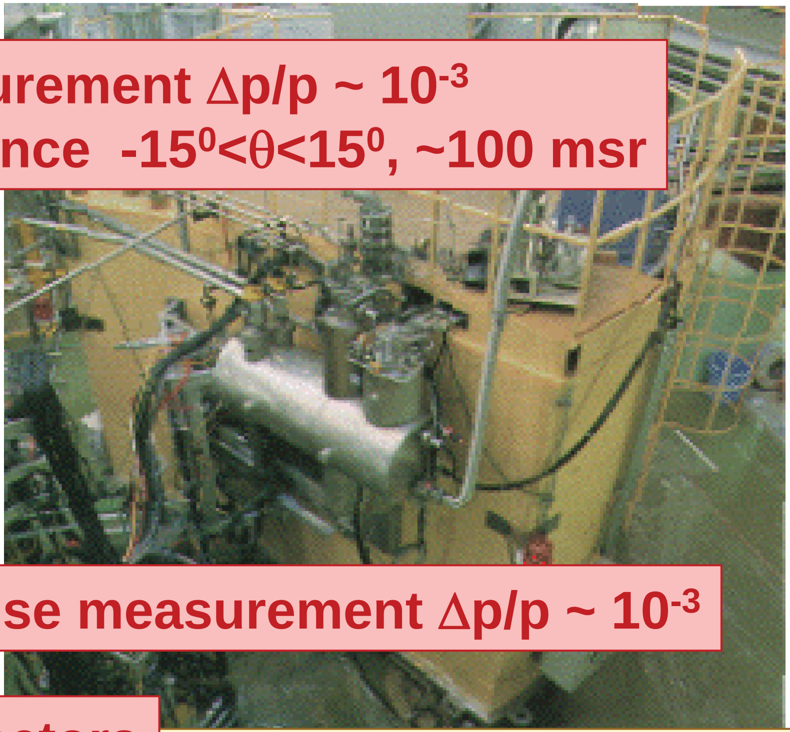
$$\pi^+ + A(^AZ) \rightarrow Hy(^A_\Lambda Z) + K^+$$

$$p_\pi = p_{Hy} + p_K$$

$$\sqrt{p_\pi^2 + m_\pi^2} + m_A = \sqrt{p_{Hy}^2 + m_{Hy}^2} + \sqrt{p_K^2 + m_K^2}$$



Precise measurement $\Delta p/p \sim 10^{-3}$
Large acceptance $-15^0 < \theta < 15^0$, ~100 msr

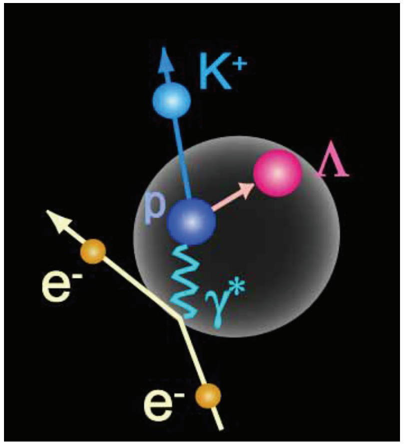


Precise measurement $\Delta p/p \sim 10^{-3}$

High-rate tracking detectors

SKS (3 T max)
(Superconducting Kaon Spectrometer)

2.2 (e,e'K^+) spectroscopy



Characteristic features of (e,e'K$^+$) experiments at JLab

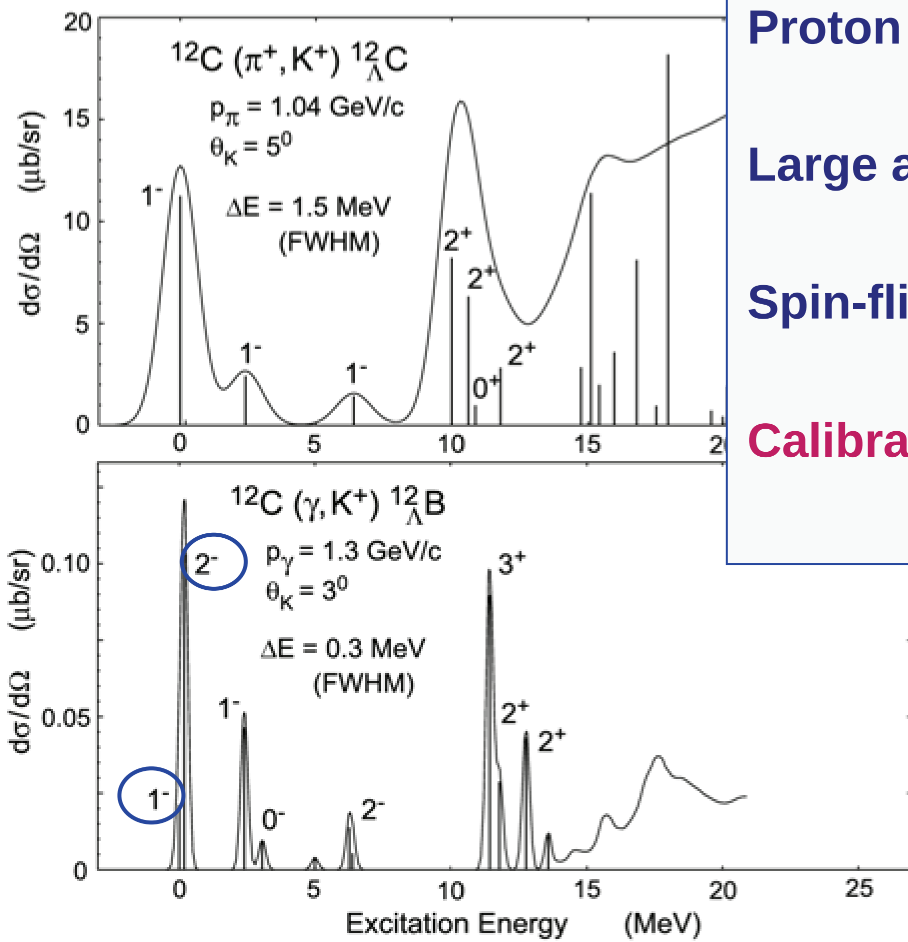
Sub MeV resolution
← High quality primary e beam

Proton to Λ → Neutron rich Λ hypernuclei
Mirror to those by (π^+,K$^+$)

Large angular momentum transfer
→ Stretched states (similar to (π^+,K$^+$))

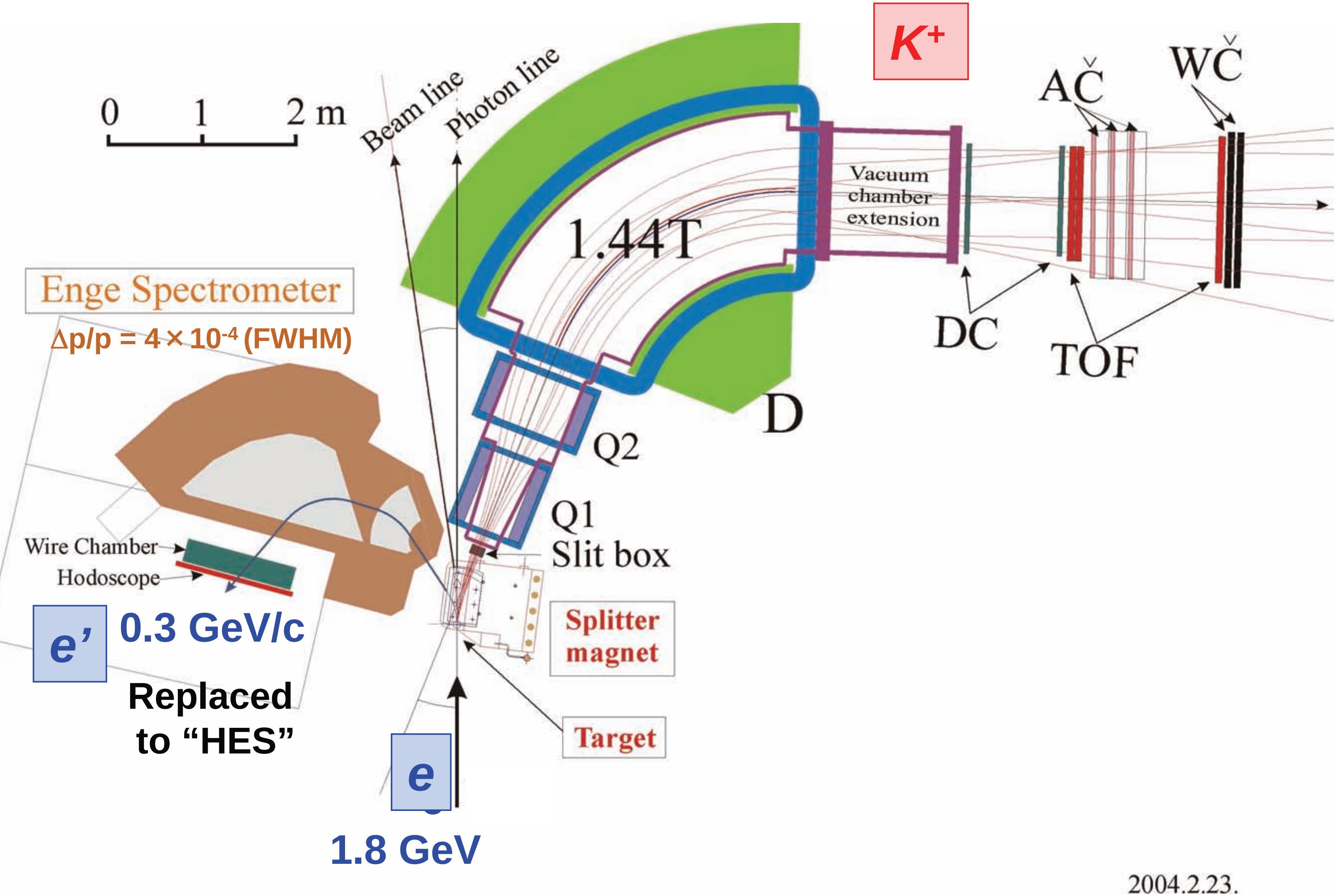
Spin-flip amplitude
→ Unnatural parity states

Calibration by p(e,eK$^+$) Σ, Λ
-> Absolute mass scale accurately

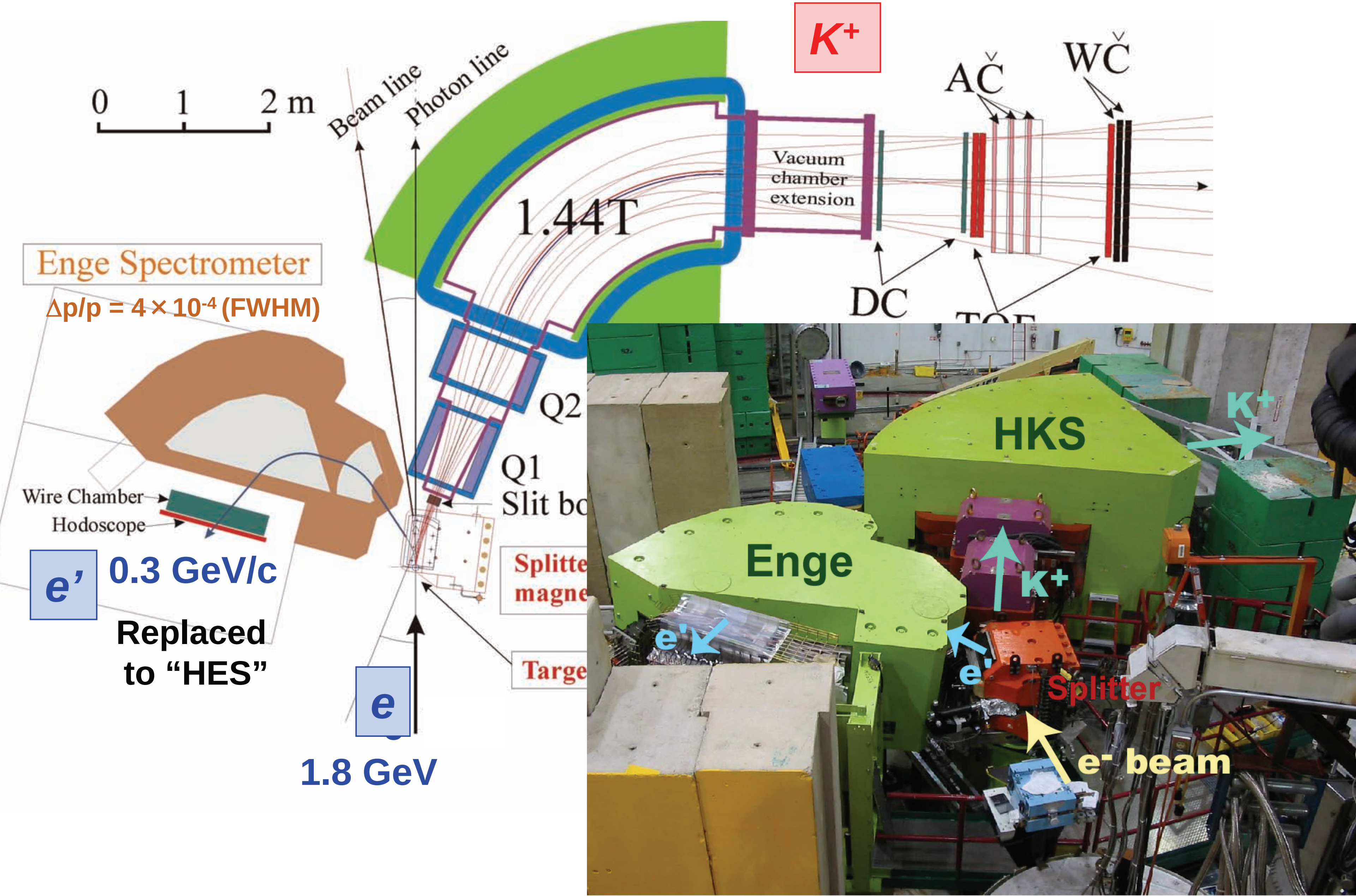


High quality e^- beam necessary
-> Jefferson Lab (Hall A and C)

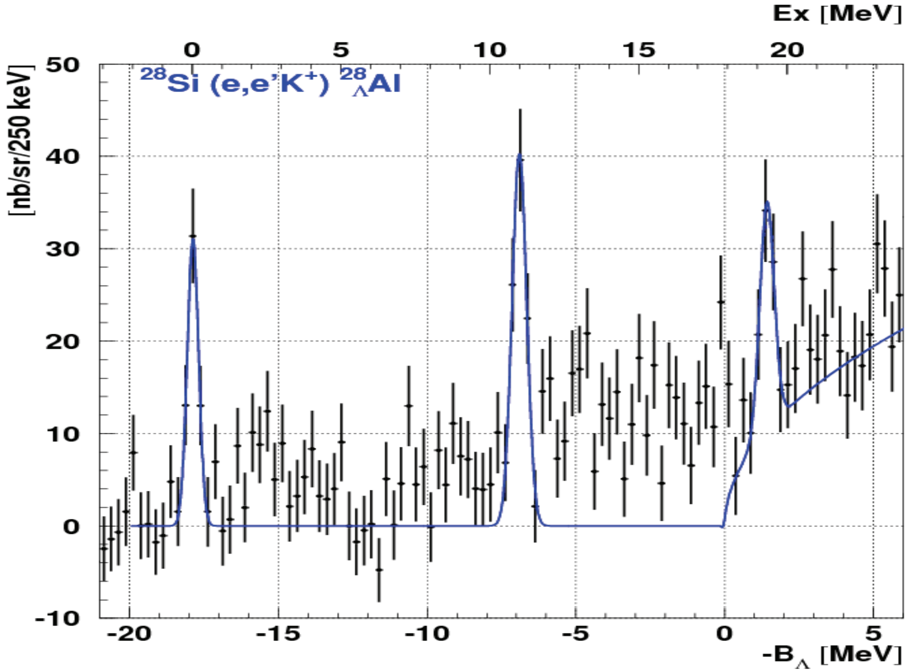
Dedicated spectrometer at Hall C



Dedicated spectrometer at Hall C

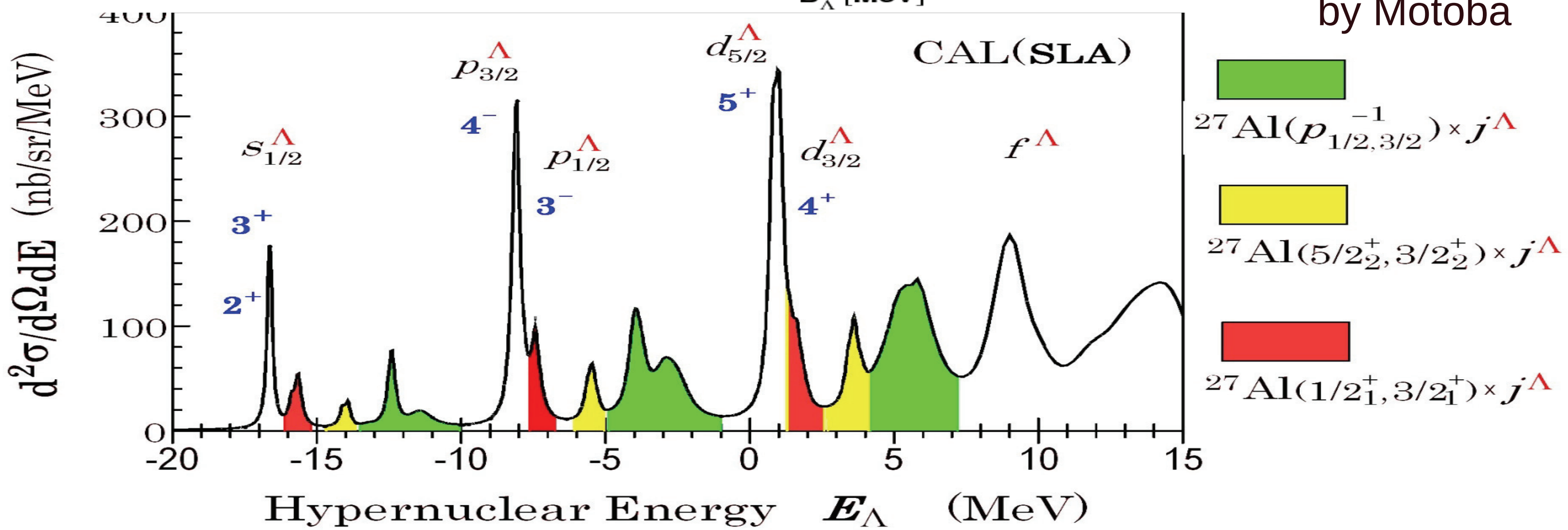


Reaction spectrum on ^{28}Si target



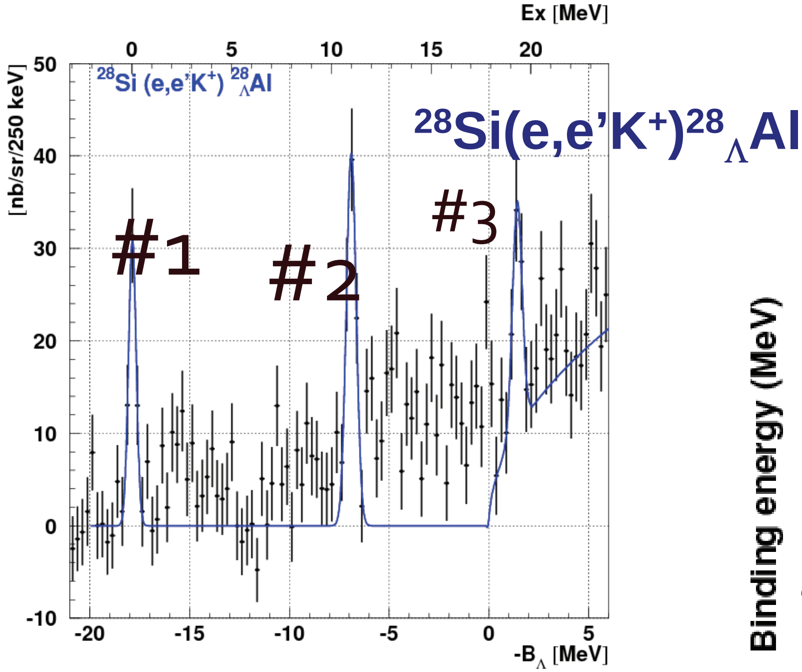
^{28}Si(e,e'K$^+$)$^{28}{}_{\Lambda}$Al reaction

Full space
$(0d_{5/2}0d_{3/2}1s_{1/2})_{pn}$ [11,12]
DWIA
YNG interaction
by Motoba

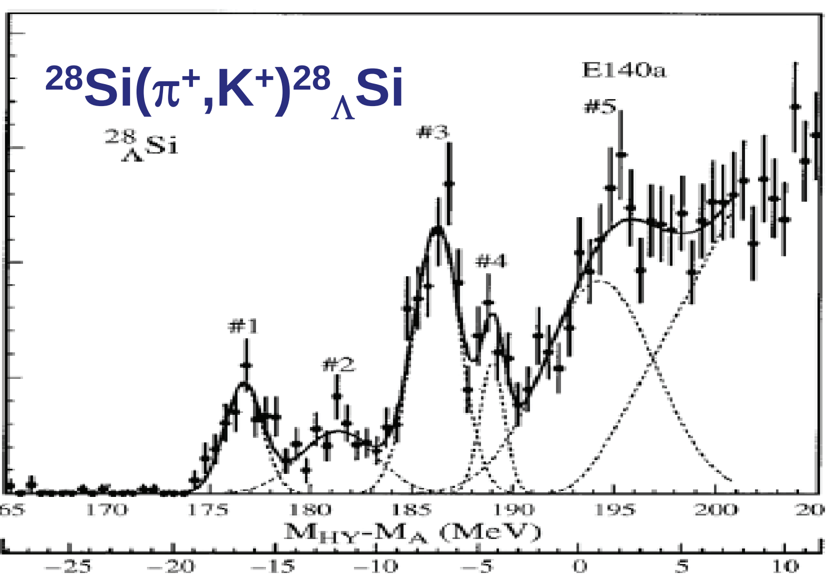


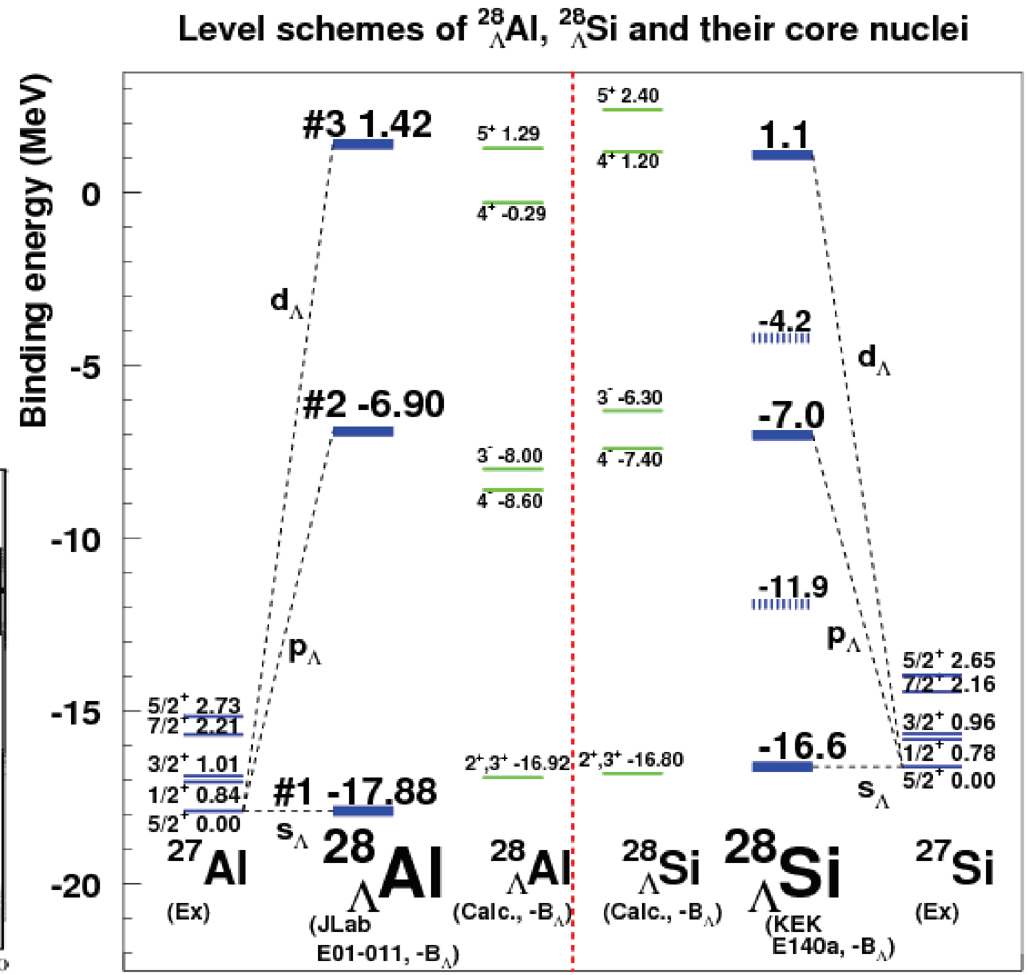
Major peak series : $[^{27}\mathrm{Al}(5/2^+_1) \times j^{\Lambda}]_J$ with $j^{\Lambda} = s, p, d, \ldots$

Comparison between $^{28}_{\Lambda}$Al and $^{28}_{\Lambda}$Si



First sd-shell hypernuclear spectroscopy by (e,e'K$^+$)





3. γ-ray spectroscopy

3.1 Motivation, method and apparatus

Reaction spectroscopy and γ-ray spectroscopy

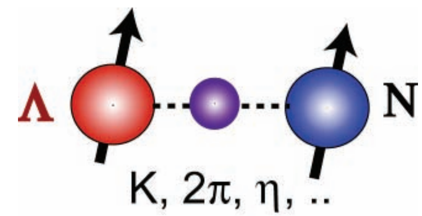
Reaction Spectroscopy	γ-Spectroscopy
Resolution: 1.5 MeV(FWHM) by (π,K^+) 0.4 MeV(FWHM) by $(e,e'K^+)$	Resolution: ~0.1 MeV (FWHM) by scintillator (NaI) 0.002 MeV (FWHM) by Ge
Bound and unbound states with width < 10 MeV	Only bound states without particle decays but faster than weak decays(10^{-10}s) -> ~~Σ, Ξ hypernuclei~~ $\Sigma N \to \Lambda N$, $\Xi N \to \Lambda\Lambda$
Absolute mass can be measured (precise by $(e,e'K^+)$ and (K^-,π^0))	Excitation energies only
Angular distributions -> ΔL -> Spin assignment	Yield, Branching ratio, $\gamma\gamma$ coincidence -> level scheme
Cross sections -> Spectroscopic factor -> wavefunction	Angular correlation, Polarization -> spin-parity assignment
	Lifetime -> Transition probabilities (B(M1),B(E2) etc.) -> wavefunction

Motivation of Hypernuclear γ Spectroscopy

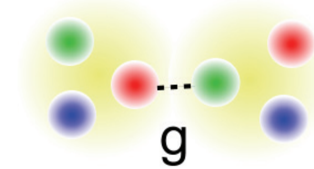
High-precision (ΔE～a few keV) spectroscopy with Ge detectors

1. YN, YY interactions

-> Unified picture of B-B interactions
Understand short-range nuclear forces
ΛN spin-dependent forces, ΣN-ΛN force, …
Understand high density nuclear matter (n-star)



At a short distance

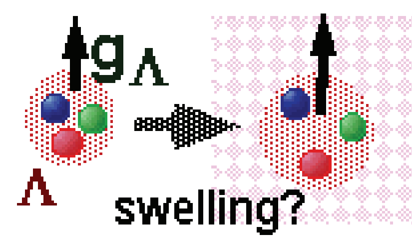


2. Impurity effects in nuclear structure

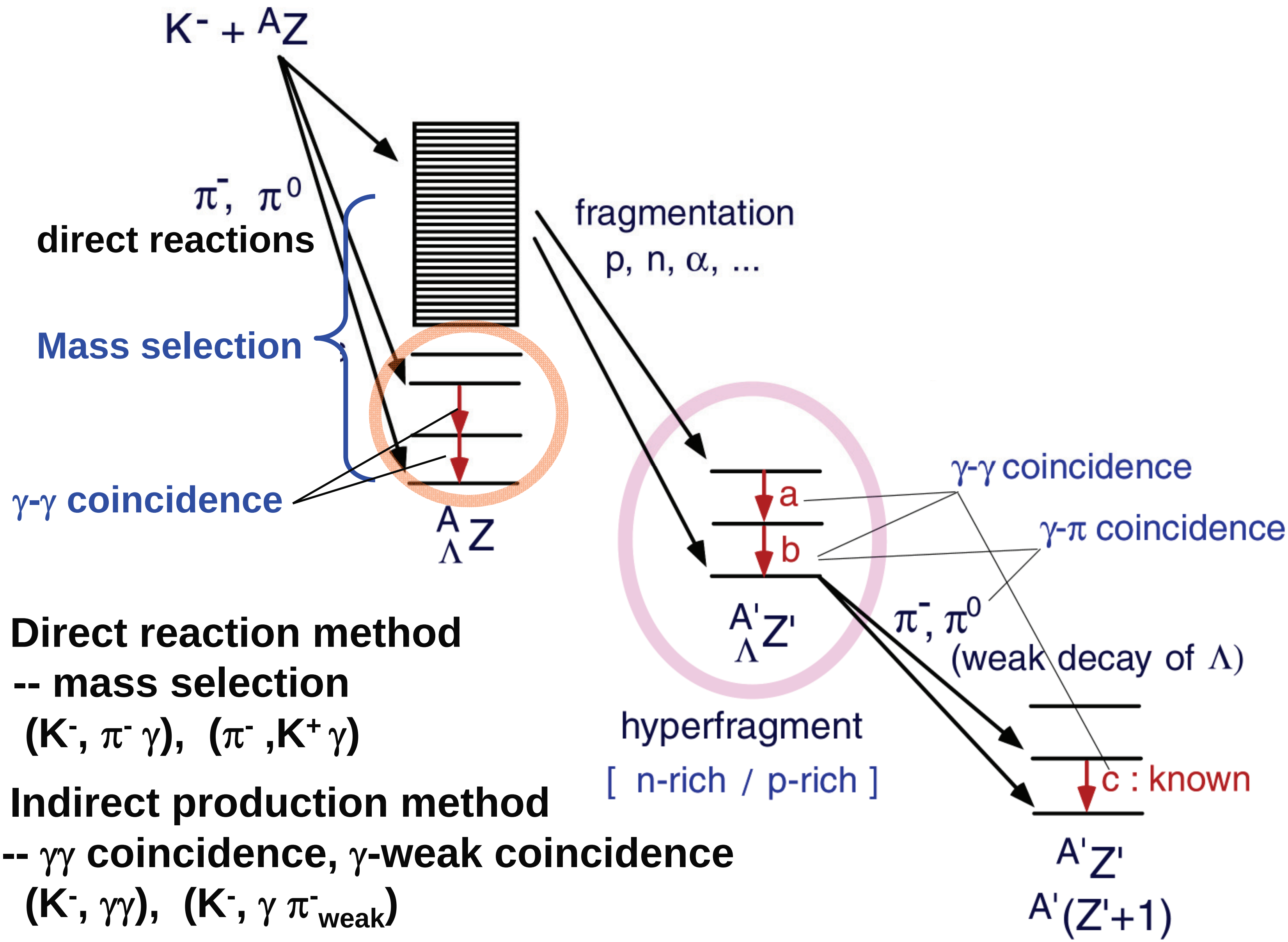
Changes of size/shape, symmetry, cluster/shell structure,..
B(E2) -> shrinking effect

3. Medium effects of baryons probed by hyperons

B(M1) -> μ_Λ in nucleus



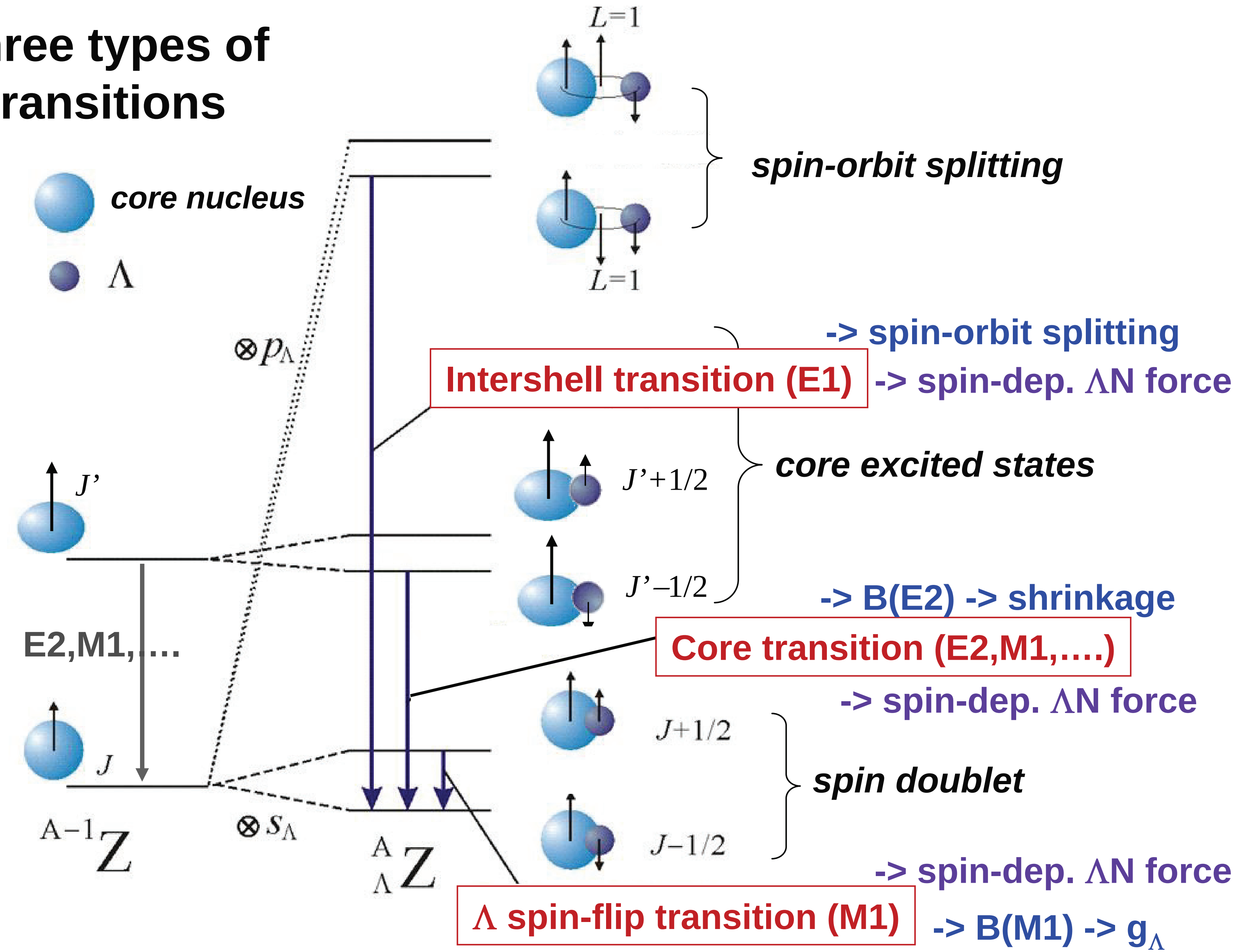
Method: How to identify hypernuclear γ rays



- **Direct reaction method**
  -- mass selection
  (K^-, π^- γ), (π^- ,K^+ γ)
- **Indirect production method**
  -- γγ coincidence, γ-weak coincidence
  (K^-, γγ), (K^-, γ π^-_{weak})

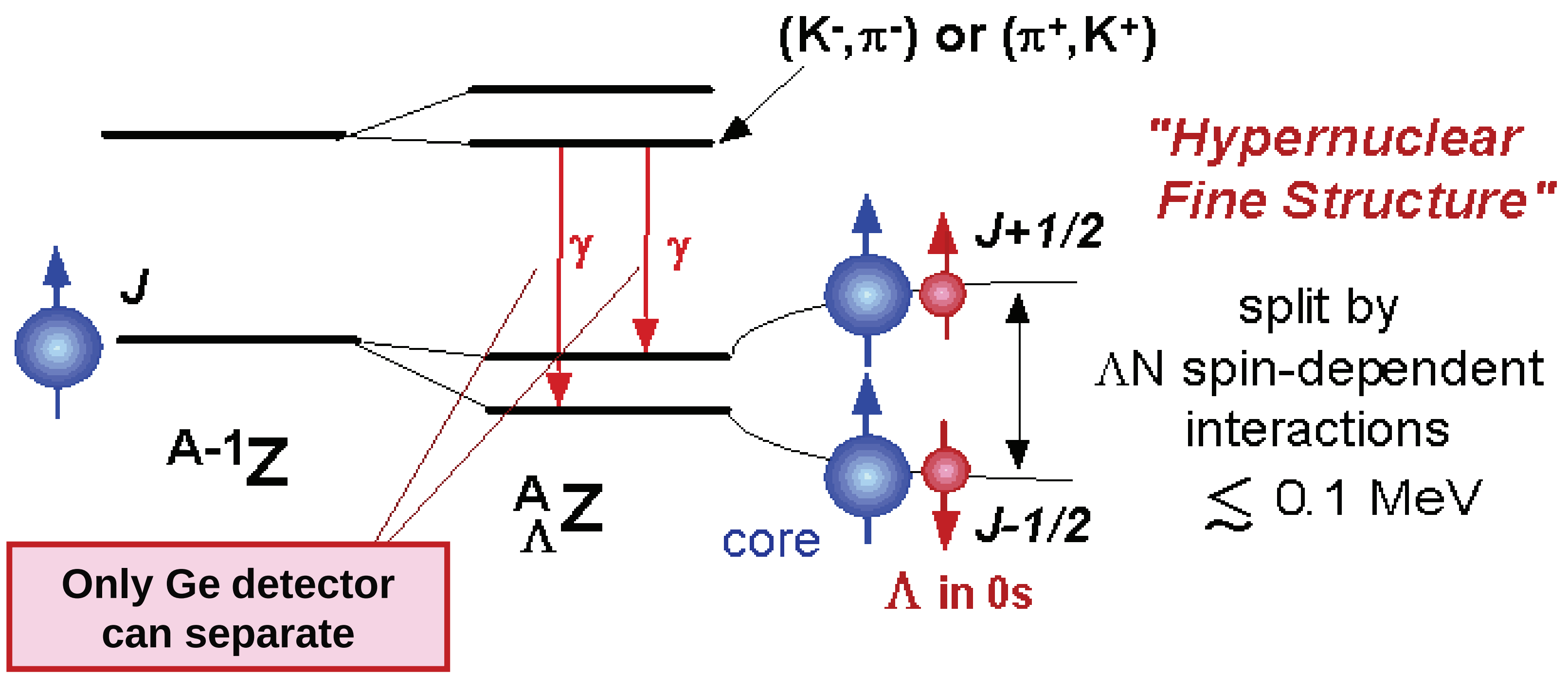
Structure of Λ Hypernuclei and γ spectroscopy

- Three types of γ transitions



Fine structure of Λ Hypernuclei and γ spectroscopy

- Low-lying levels of Λ hypernucleus



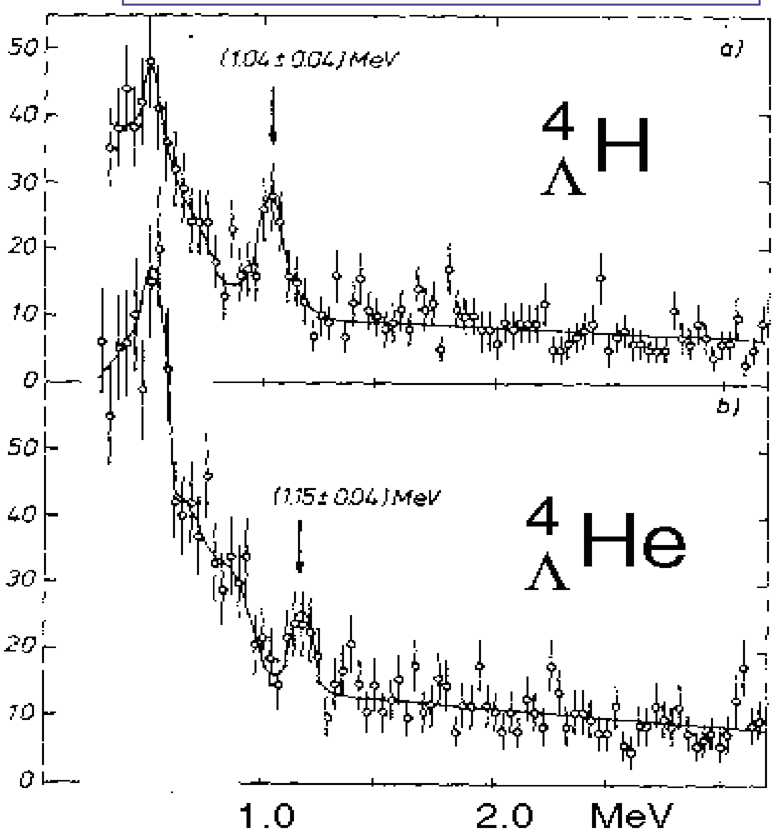
ΔE ~ 0.002 MeV FWHM by γ spectroscopy with Ge detectors

⇔ *ΔE* ~ 1.5 MeV FWHM by (π^+,K^+)
~ 0.4 MeV FWHM by $(e,e'K^+)$

Past experiments before Hyperball (1998~)

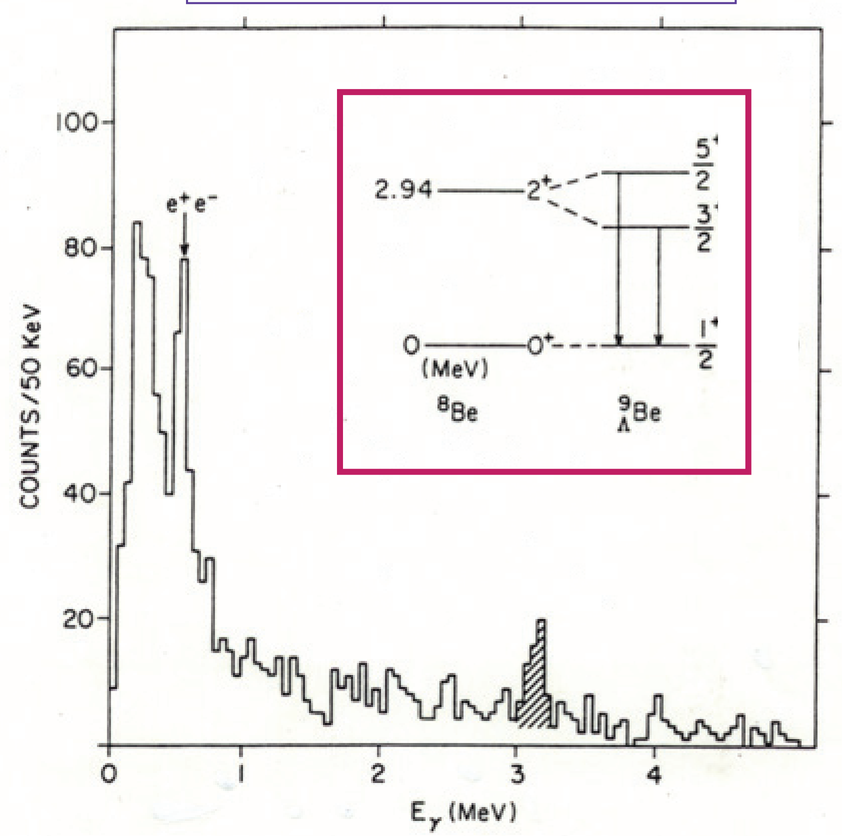
- **Only 5 γ transitions, All by NaI counters (ΔE ~ 0.1 MeV at 1MeV), Low statistics**
- **No significant improvement before "Hyperball"**
- **Use of Ge detector once attempted but γ rays not observed**

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



Bedjidian et al, PLB 83 (1979) 252

^{9}Be(K$^-$,π$^-$) with NaI (1983)

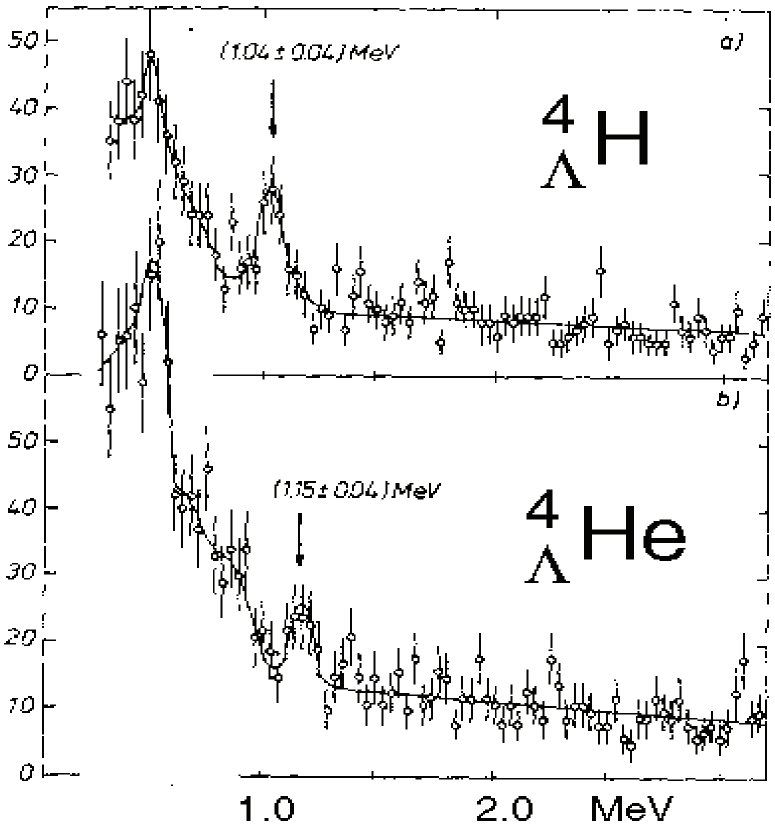


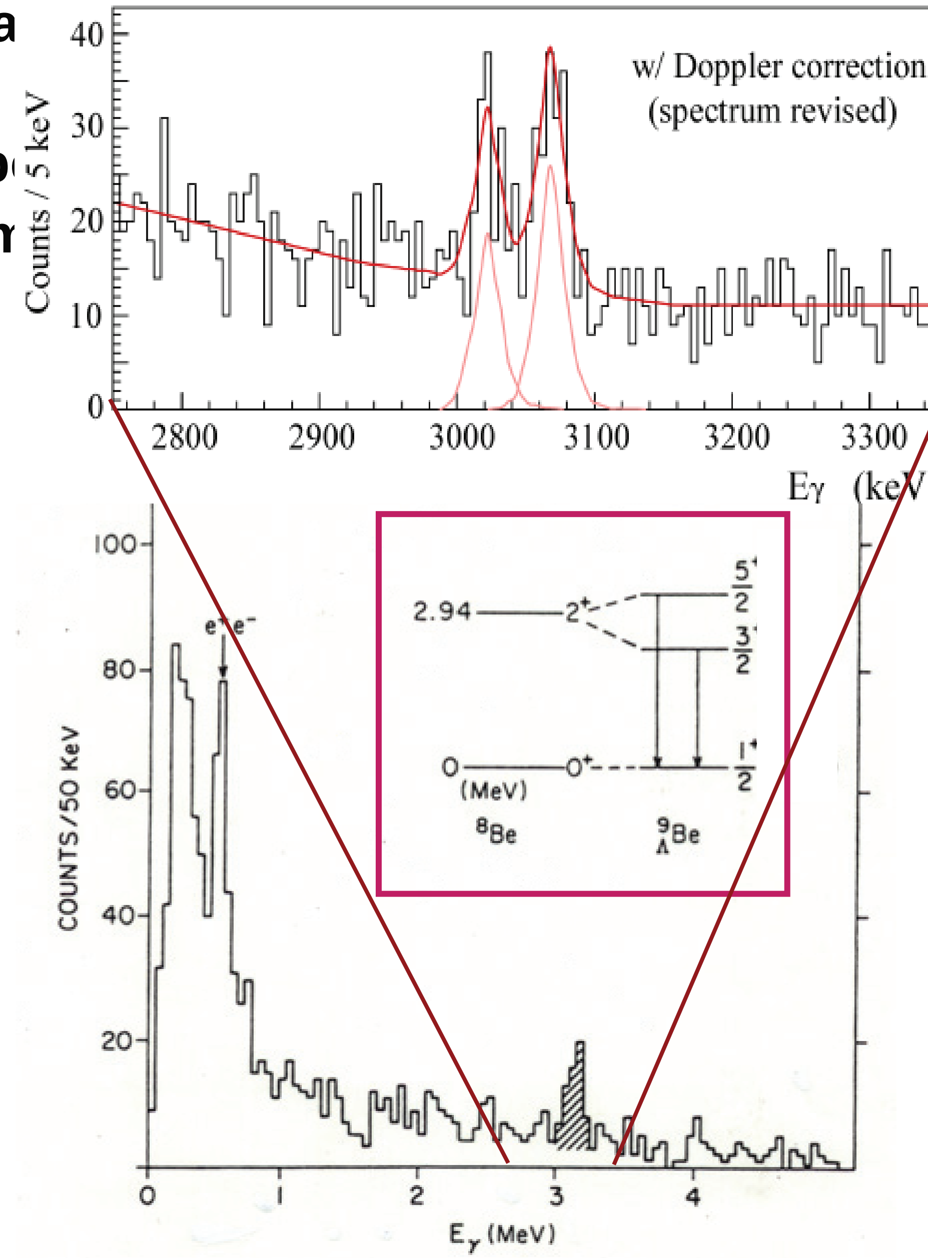
Past experiments before Hyper

Hyperball (E930)

- **Only 5 γ transitions, All by Na**
  Low statistics
- **No significant improvement b**
- **Use of Ge detector once atten**

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





Bedjidian et al, PLB 83 (1979) 252

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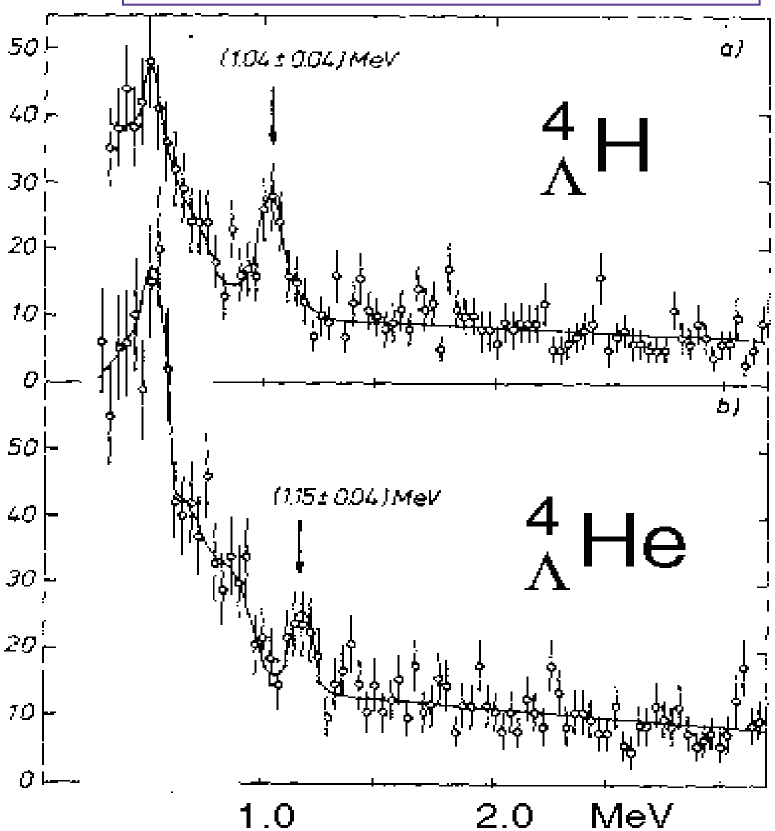
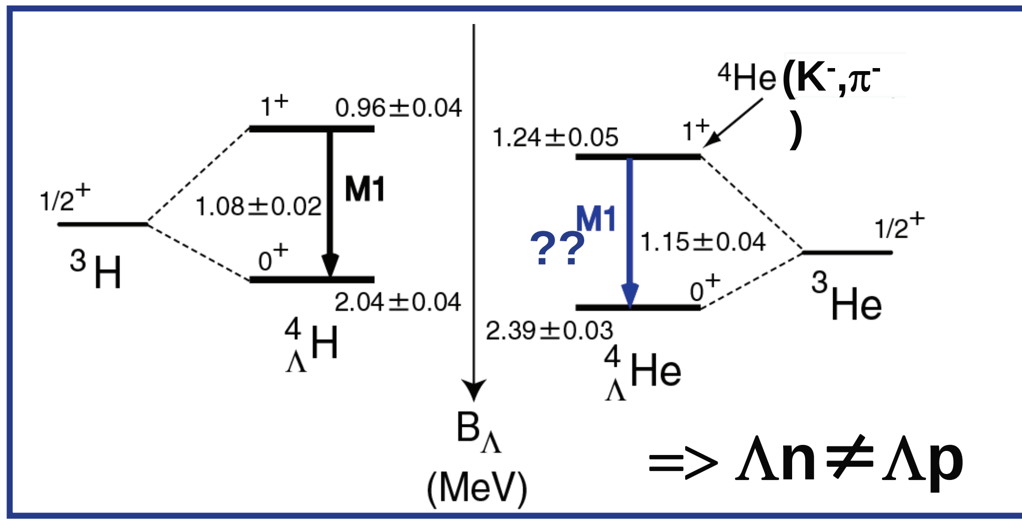


Bedjidian et al, PLB 83 (1979) 252

Another data for charge symmetry breaking

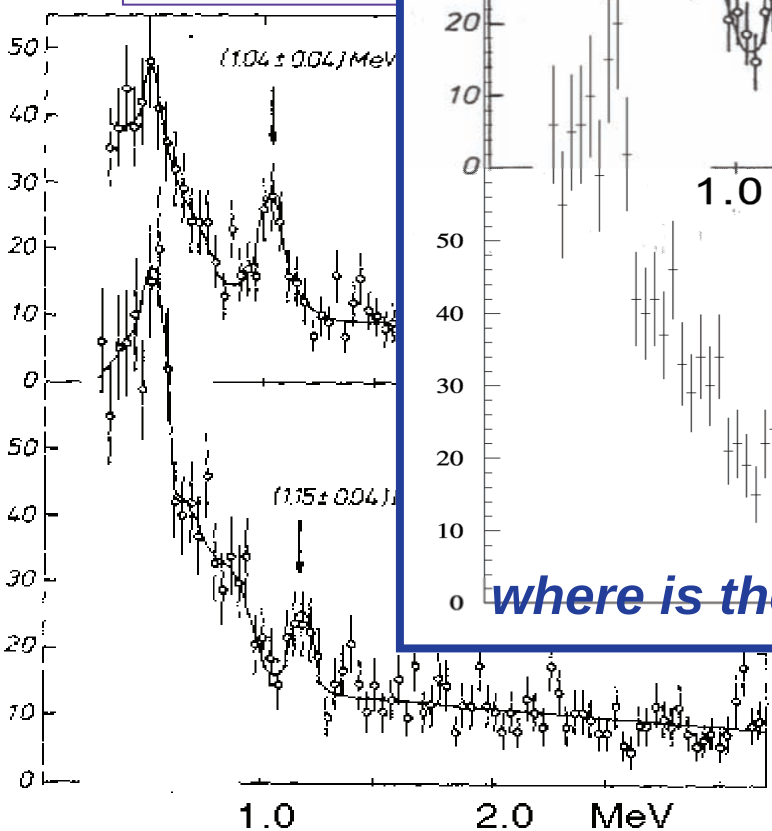


Past exp… (1998~)

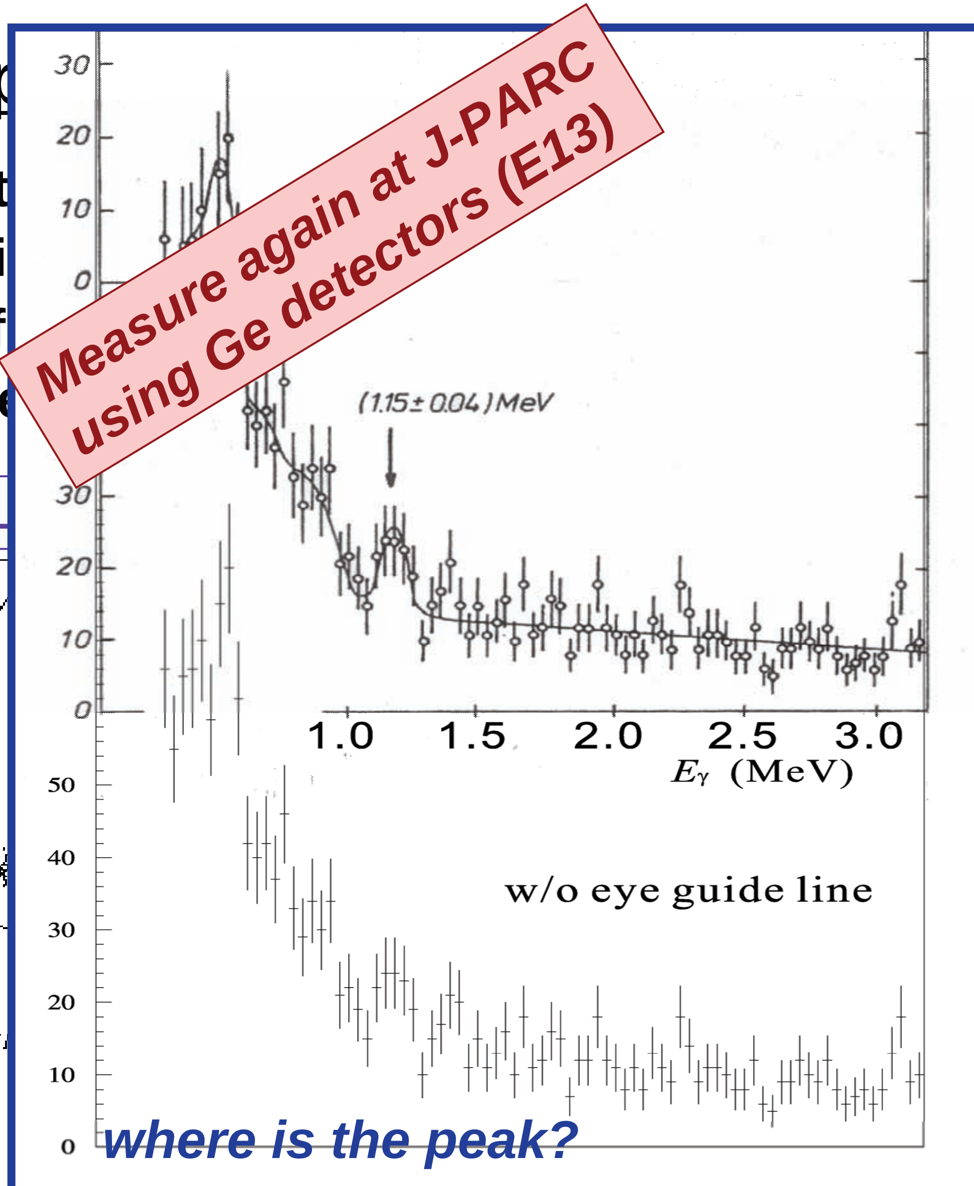
- Only 5 γ t… .1 MeV at 1MeV),
  Low stati…
- No signif…
- Use of Ge… …ot observed

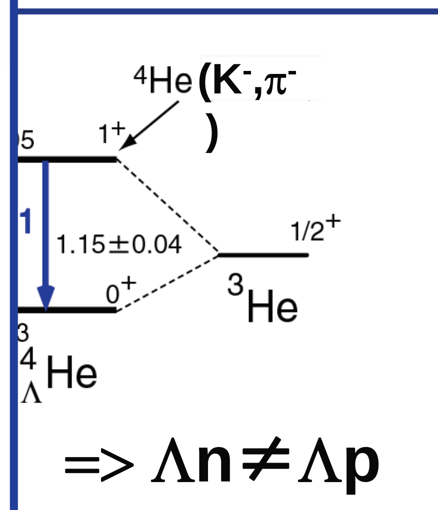
stop K^- on ^6L…

…data
…etry breaking

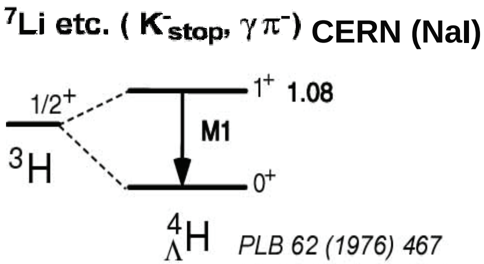


Bedjidian et al, PLB 83 (1979) 252

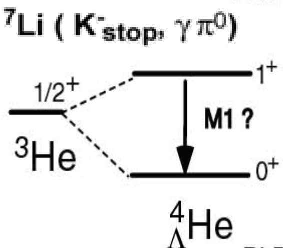




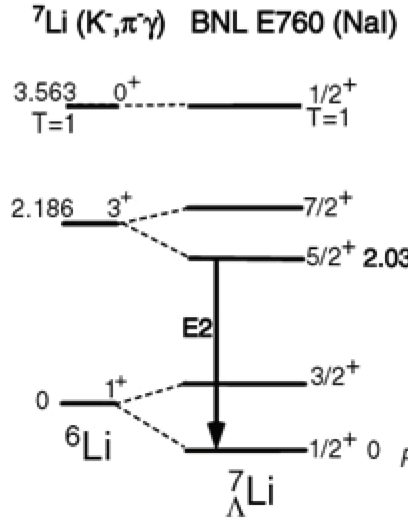
Hypernuclear γ-ray data before 1998



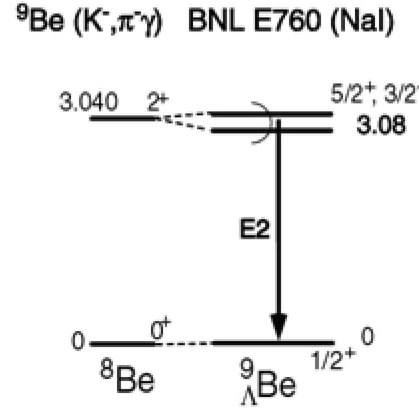
PLB 62 (1976) 467
PLB 83 (1979) 252

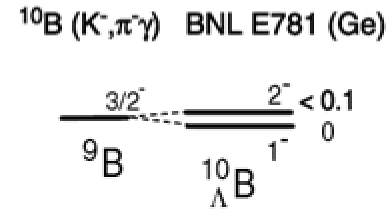


PLB 83 (1979) 252

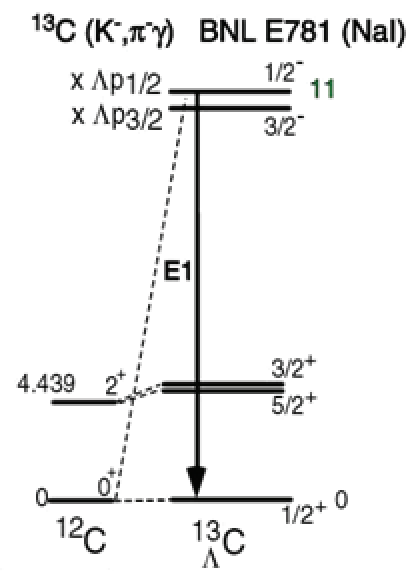


PRL 51 (1983) 2085





PRC 41 (1990) 1062

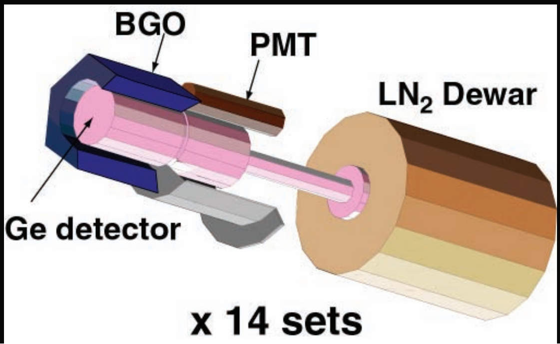


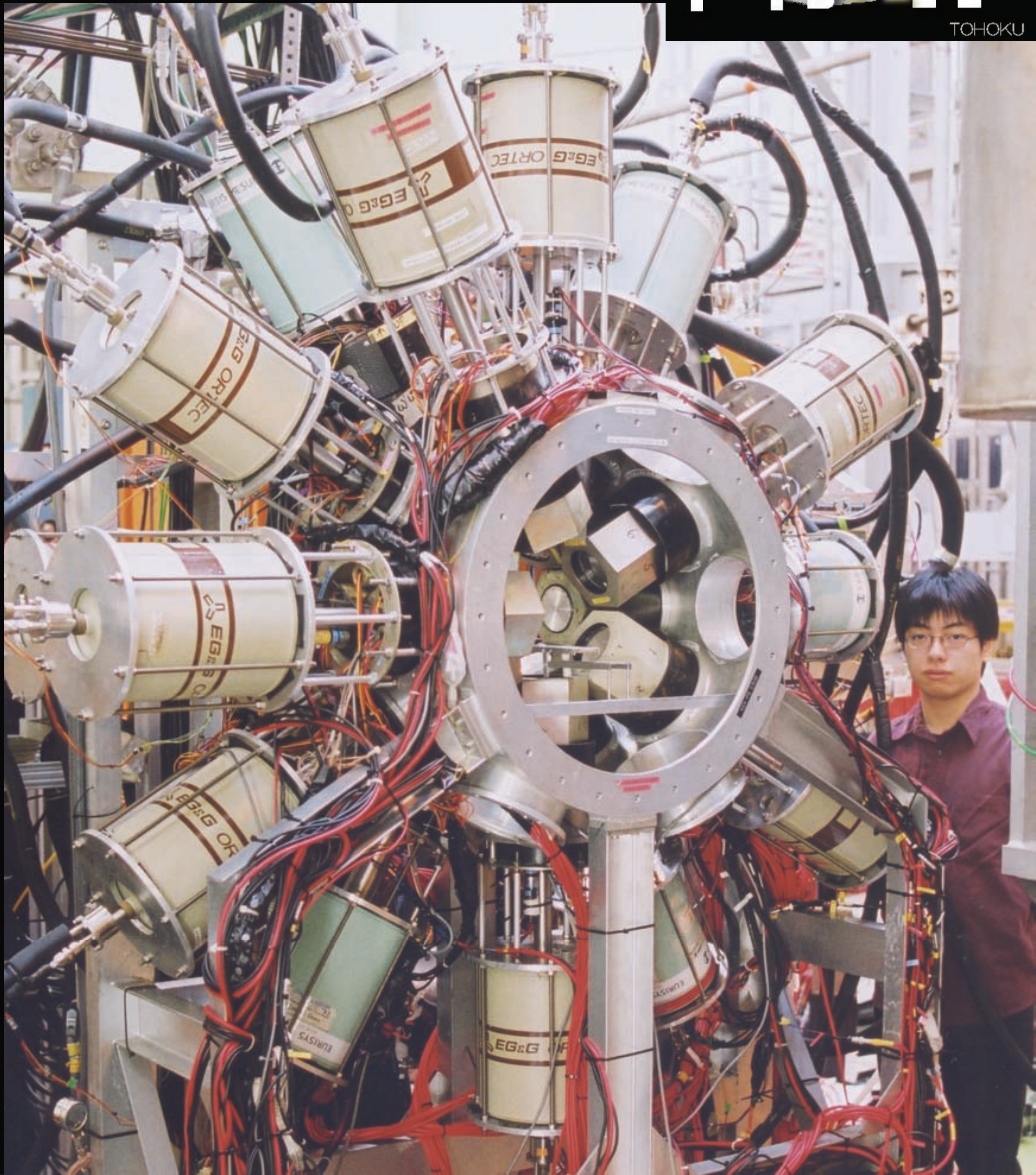
PRL 78 (1997) 4343

Hyperball (Tohoku/ Kyoto/ KEK, 1998)

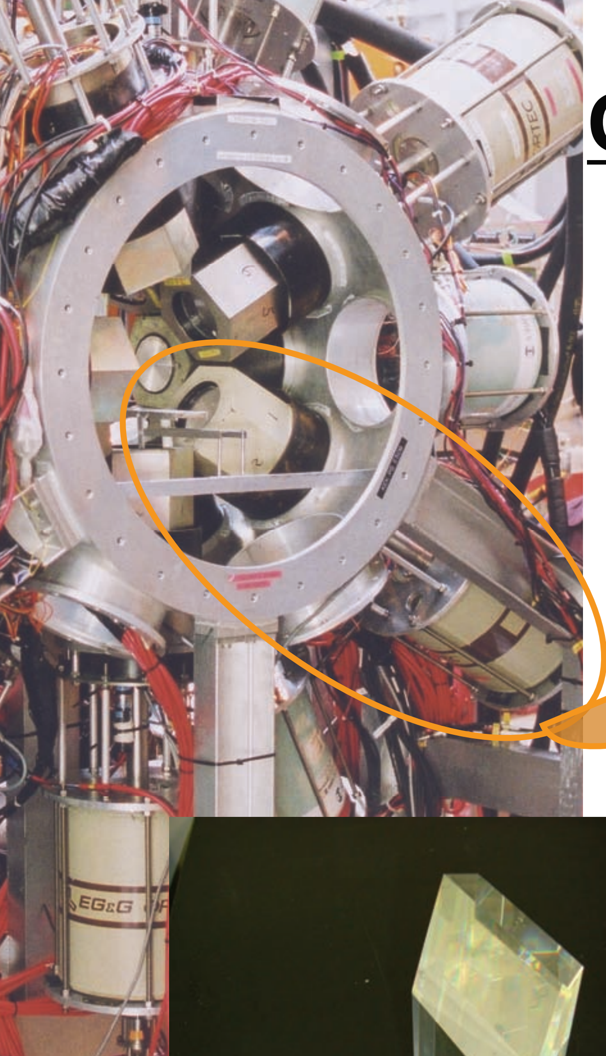
- Large acceptance for small hypernuclear γ yields
  - Ge (r.e. 60%) x 14
    - Ω ~ 15%, ε ~ 2.5% at 1 MeV
- High-rate electronics for huge background
- BGO counters for π^0 and Compton suppression

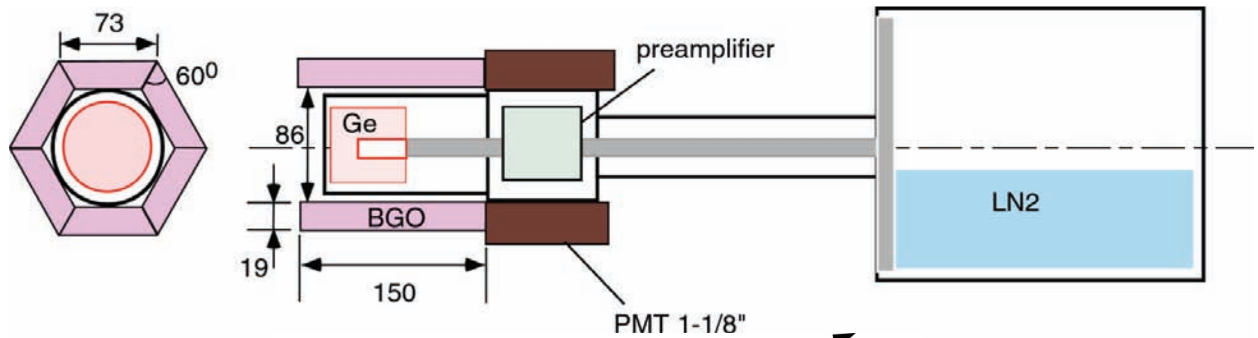
Resolution of hypernuclear spectroscopy:
1 MeV -> 2 keV FWHM

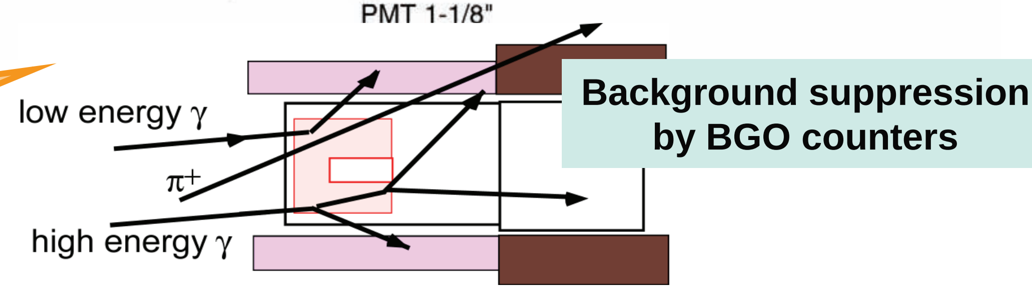


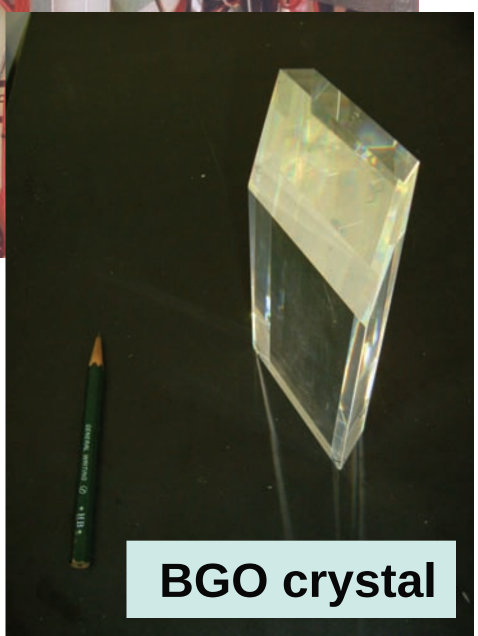


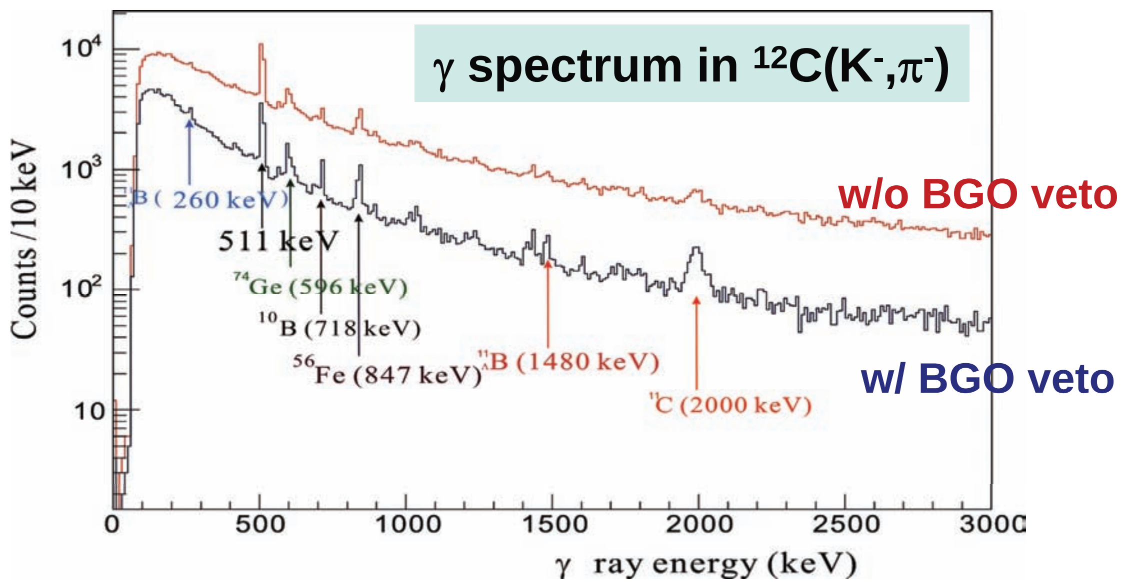
Ge detector and BGO counters



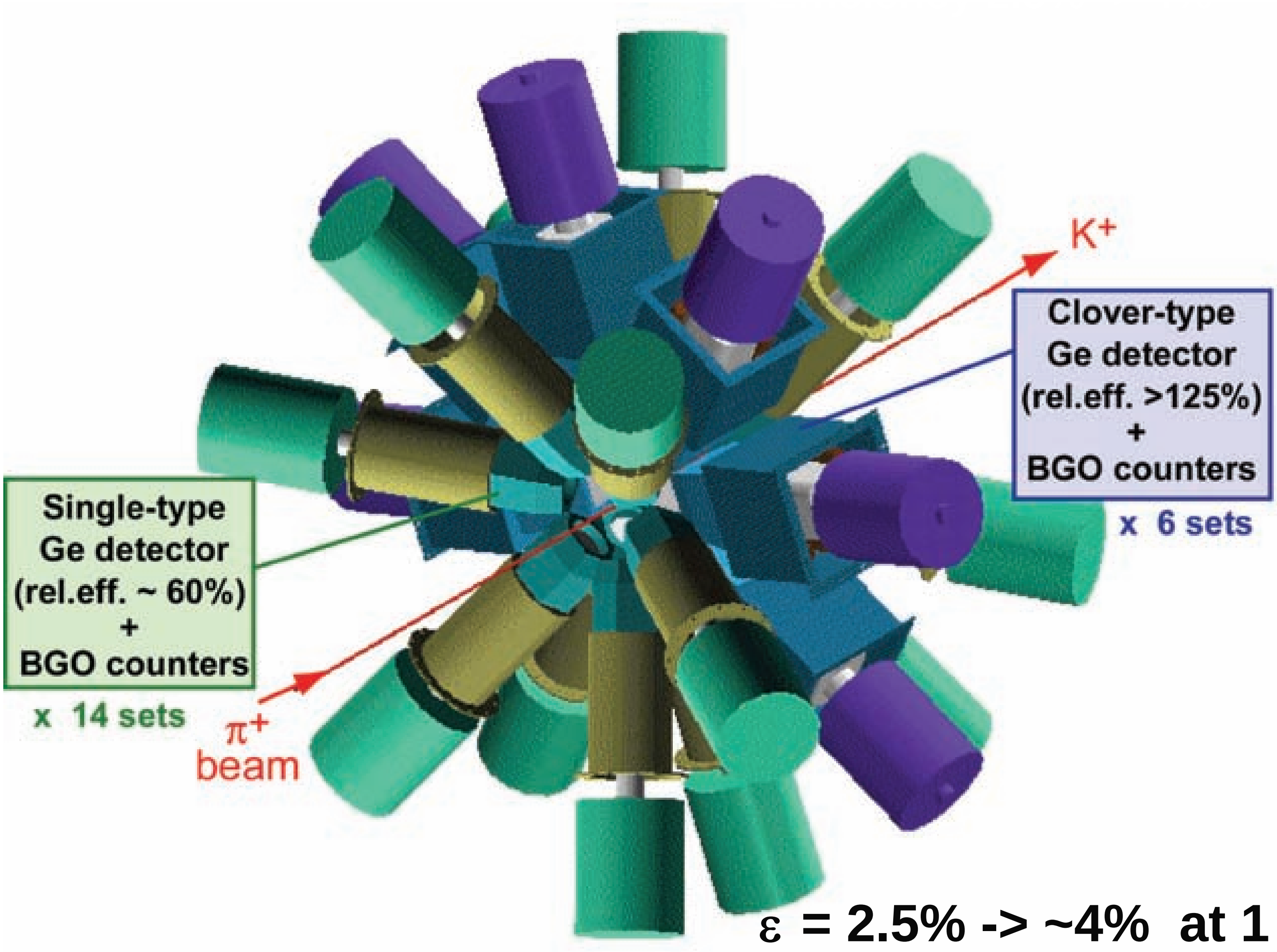






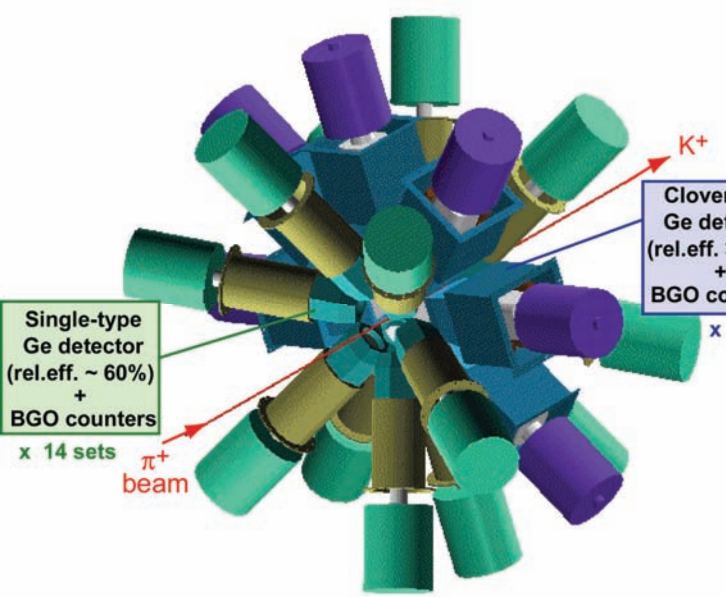


Hyperball2 (2005~)

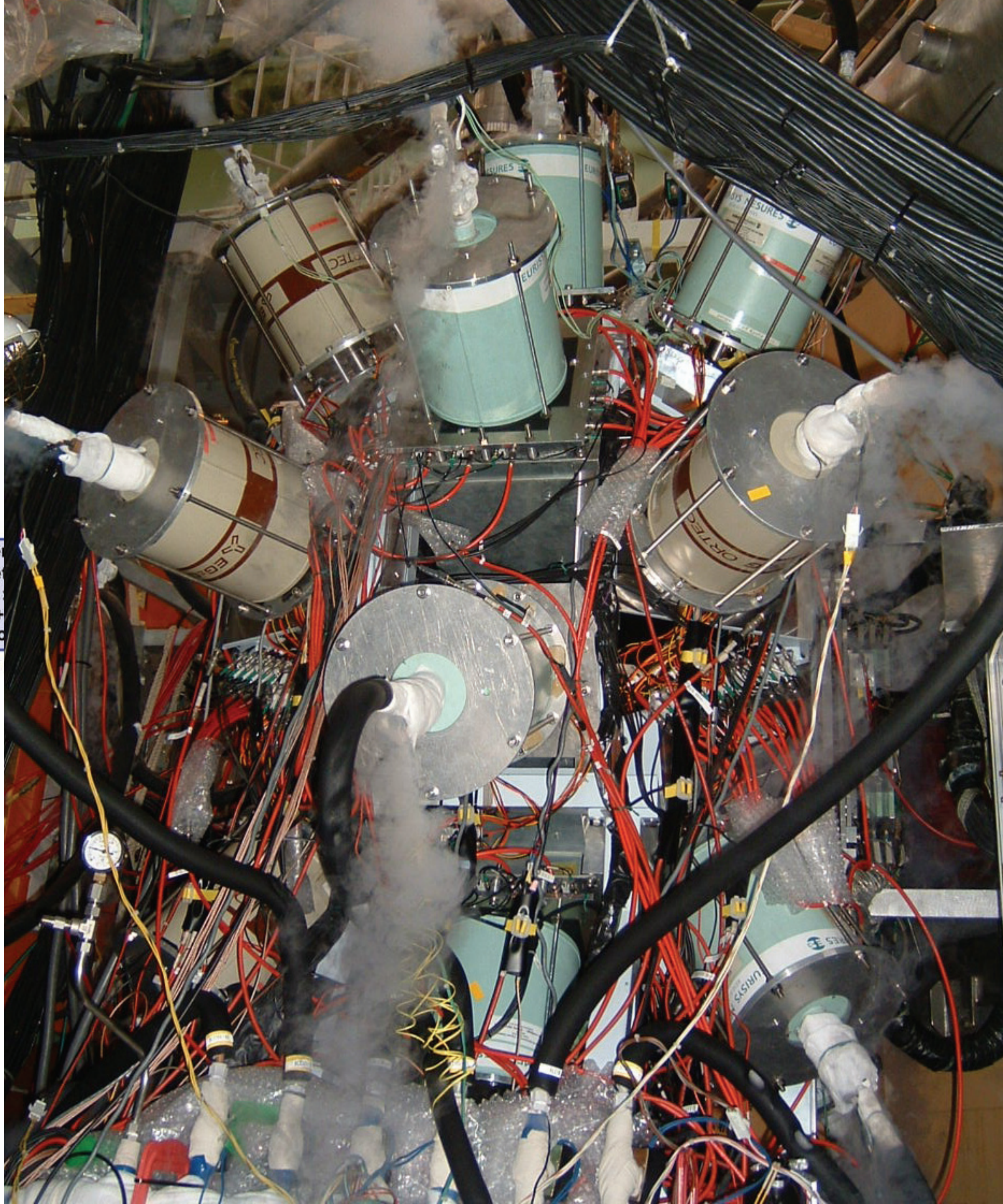


ε = 2.5% -> ~4% at 1 MeV

Hyperball2

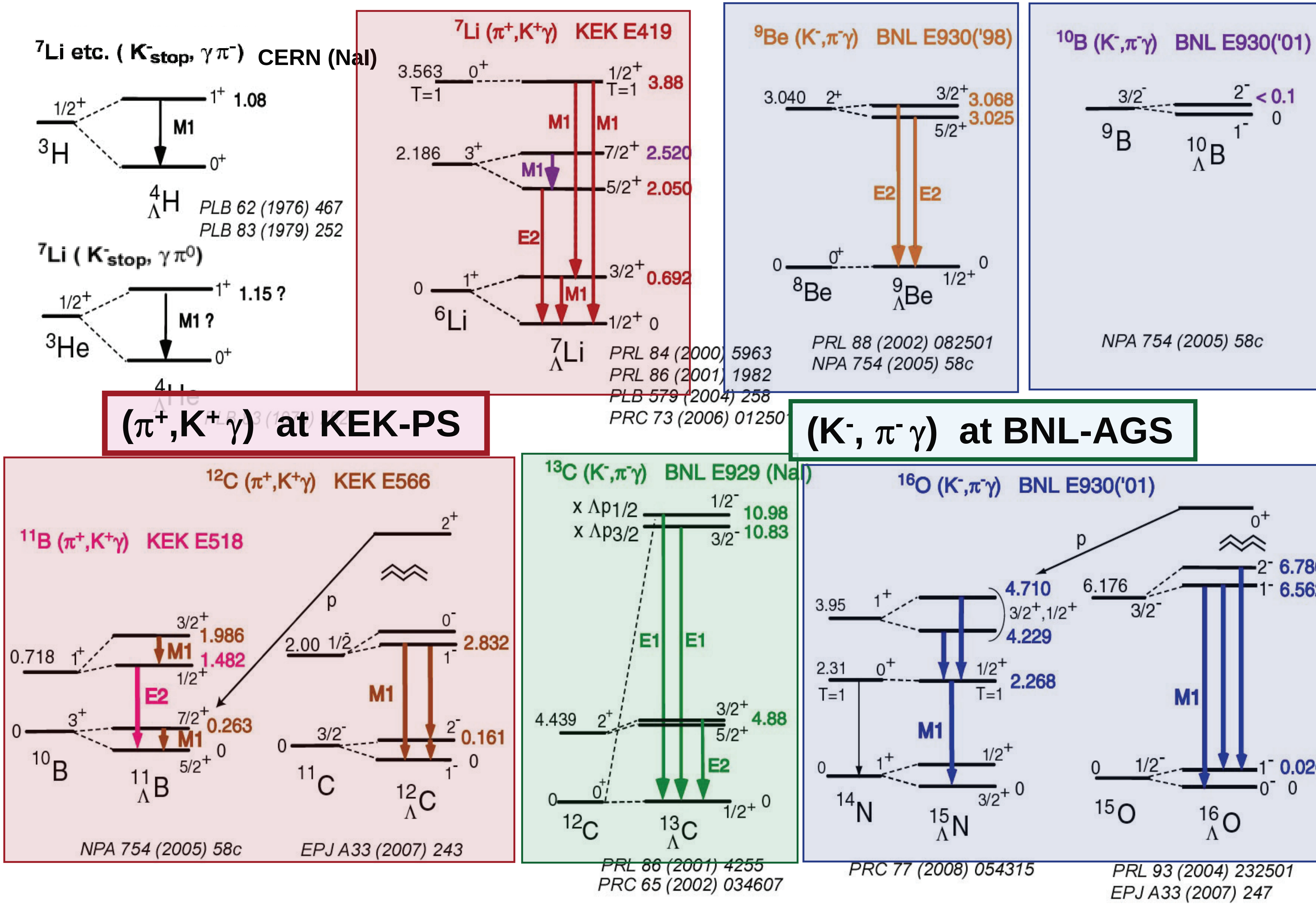


K^+
Clover
Ge det
(rel.eff.
+
BGO co
x
Single-type
Ge detector
(rel.eff. ~ 60%)
+
BGO counters
x 14 sets
π^+
beam

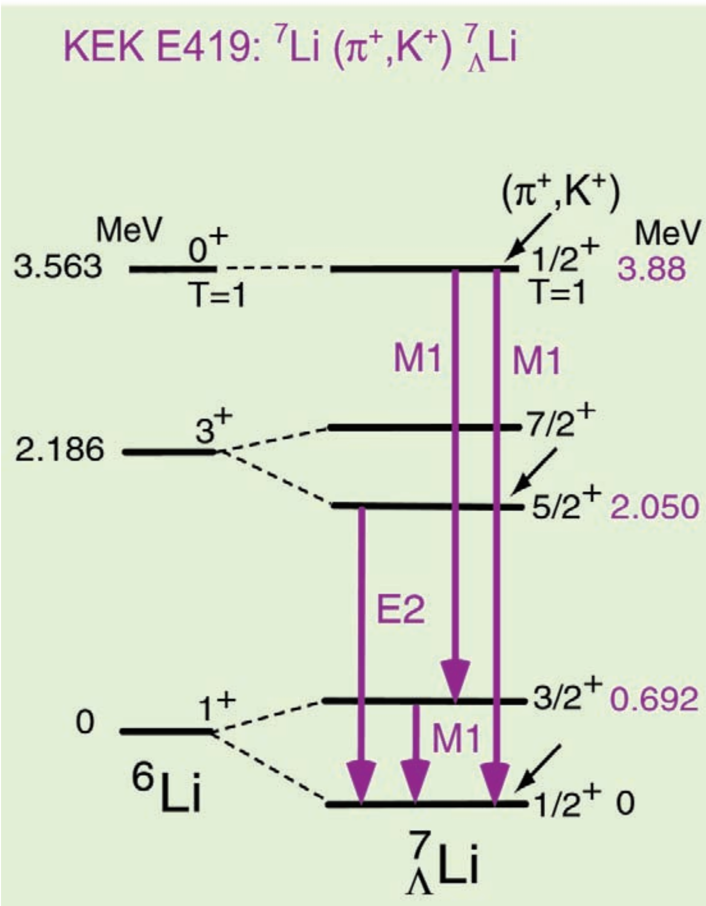


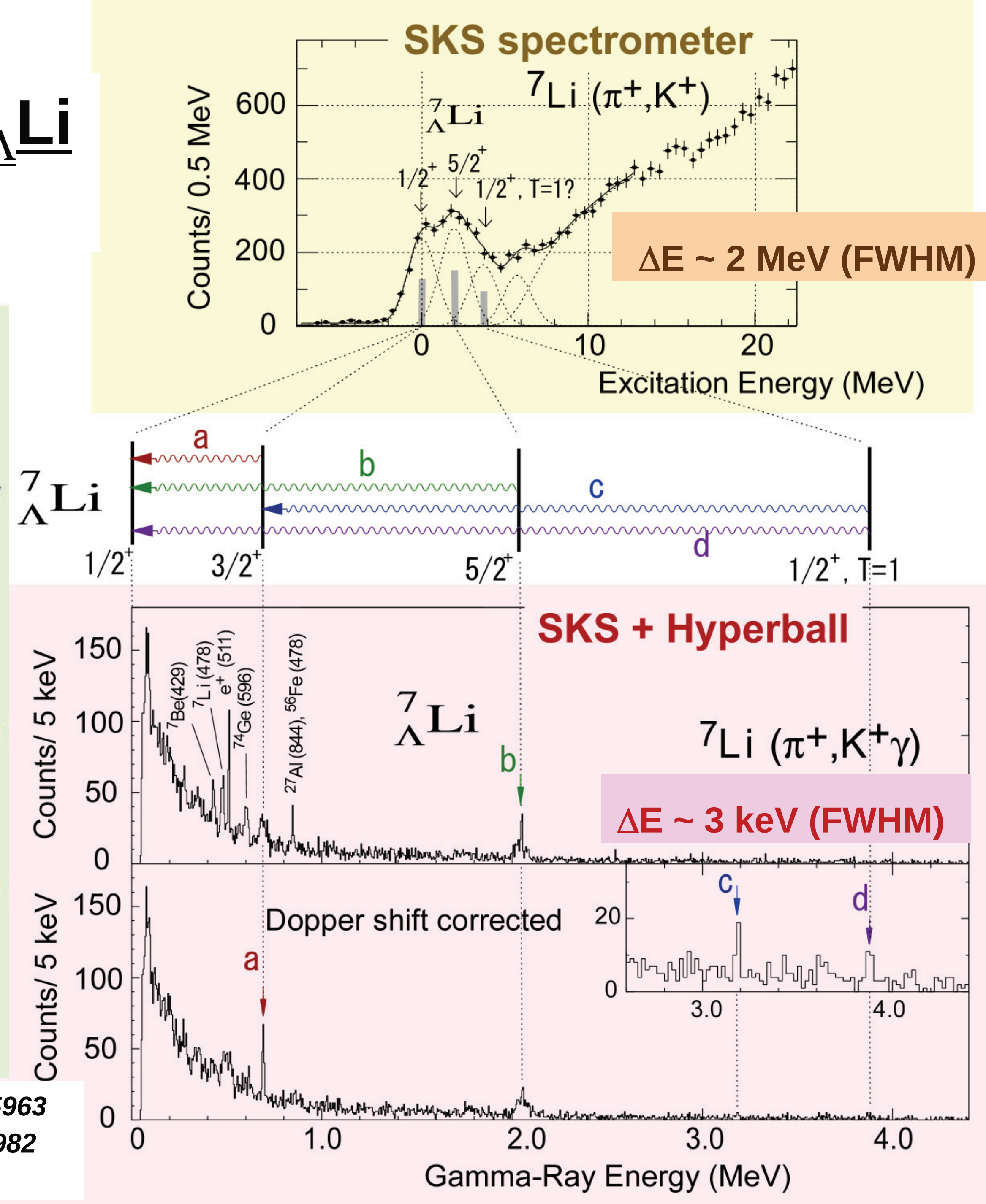
3.2 Experiments and Data

Hypernuclear γ-ray data after 1998



γ-ray spectrum of $^{7}_{\Lambda}$Li
(KEK E419)



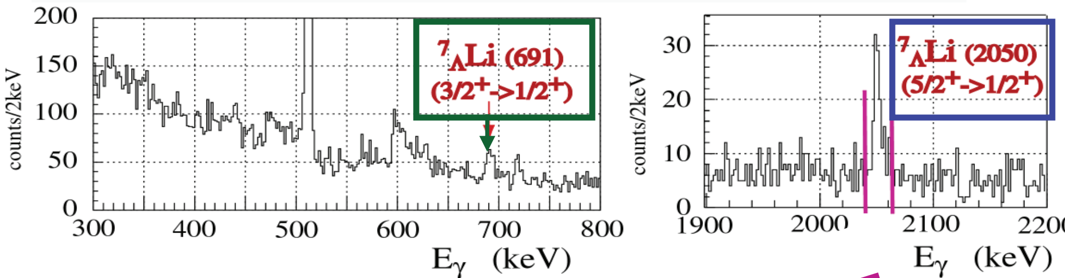


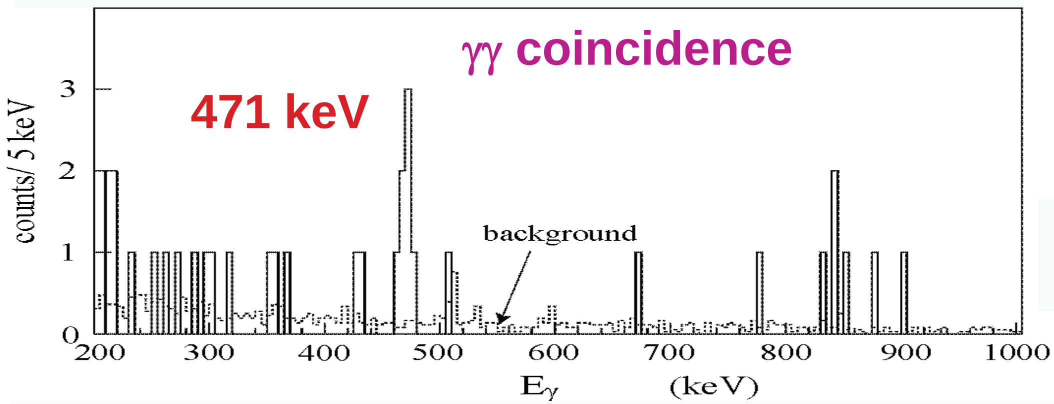
H. Tamura et al., Phys. Rev. Lett. 84 (2000) 5963
K. Tanida et al., Phys. Rev. Lett. 86 (2001) 1982
J. Sasao et al., Phys. Lett. B 579 (2004) 258

$\gamma\gamma$ coincidence in $^{7}_{\Lambda}$Li

BNL E930('01)

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



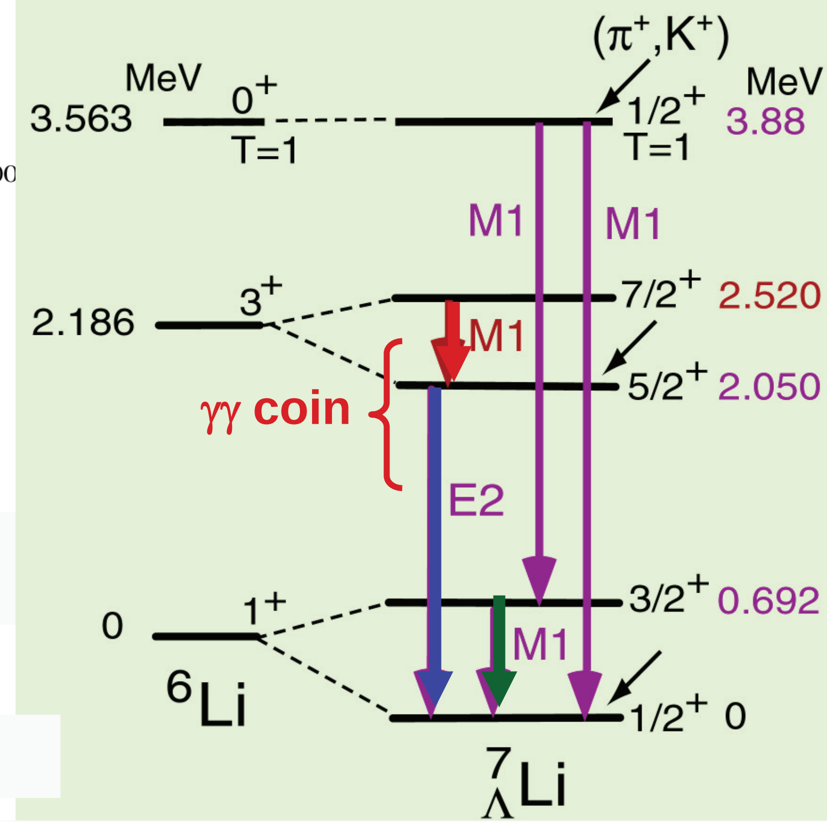


First $\gamma\gamma$ coincidence for hypernuclei

Ukai et al., PRC 73 (2006) 012501

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

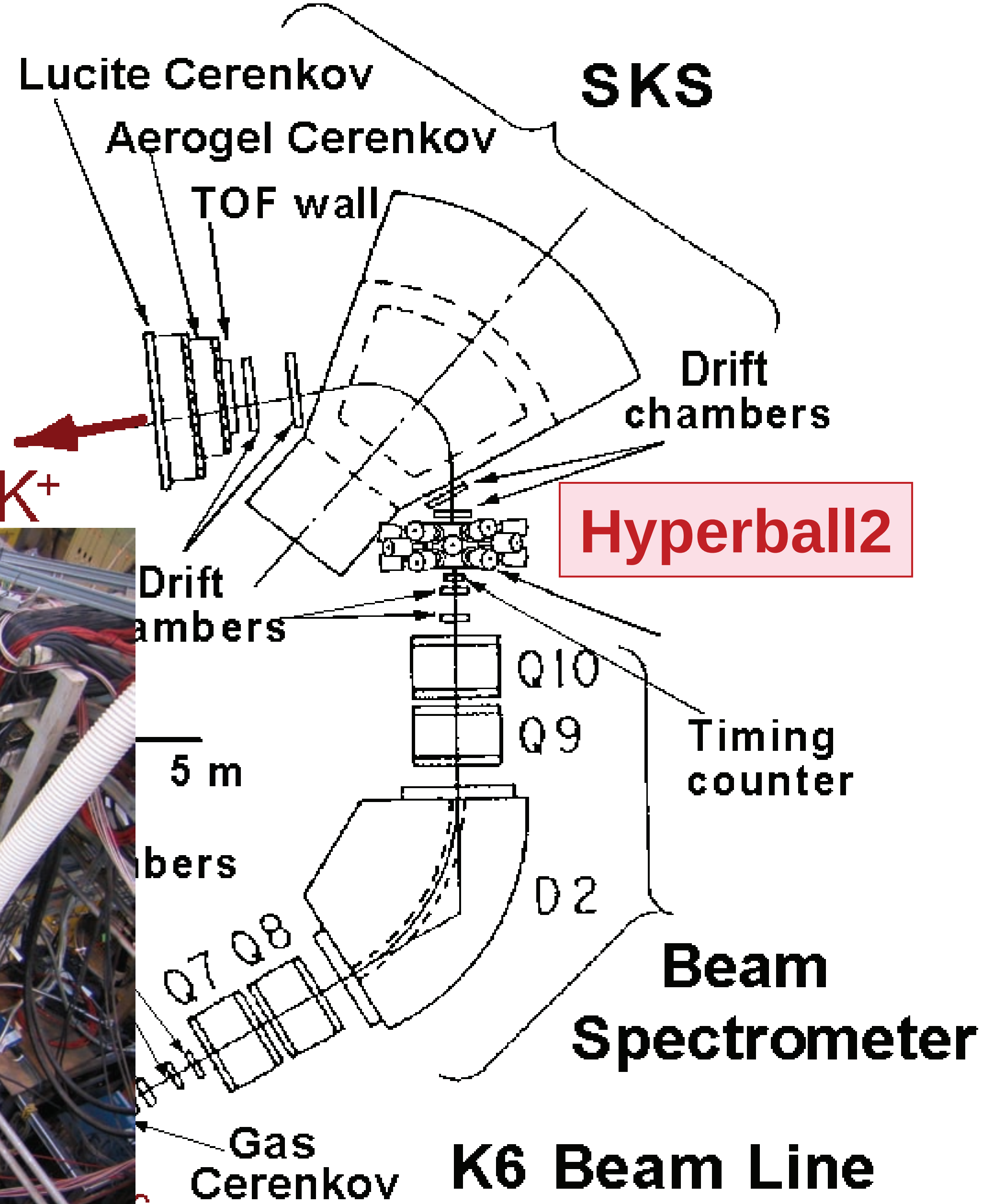
BNL E930-2: ^{10}B (K$^-$,π^-)$^{10}_{\Lambda}$B* -> $^{7}_{\Lambda}$Li*

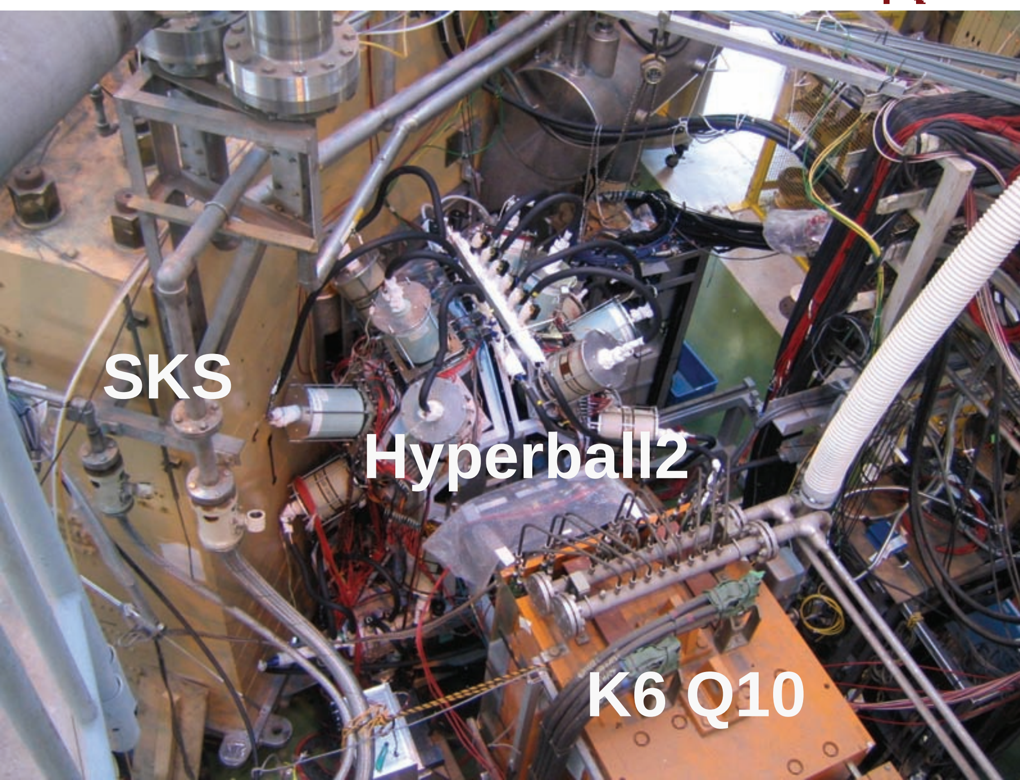


All the bound states determined

$^{12}C\ (\pi^+,K^+)\ ^{12}{}_{\Lambda}C$ (KEK E566)

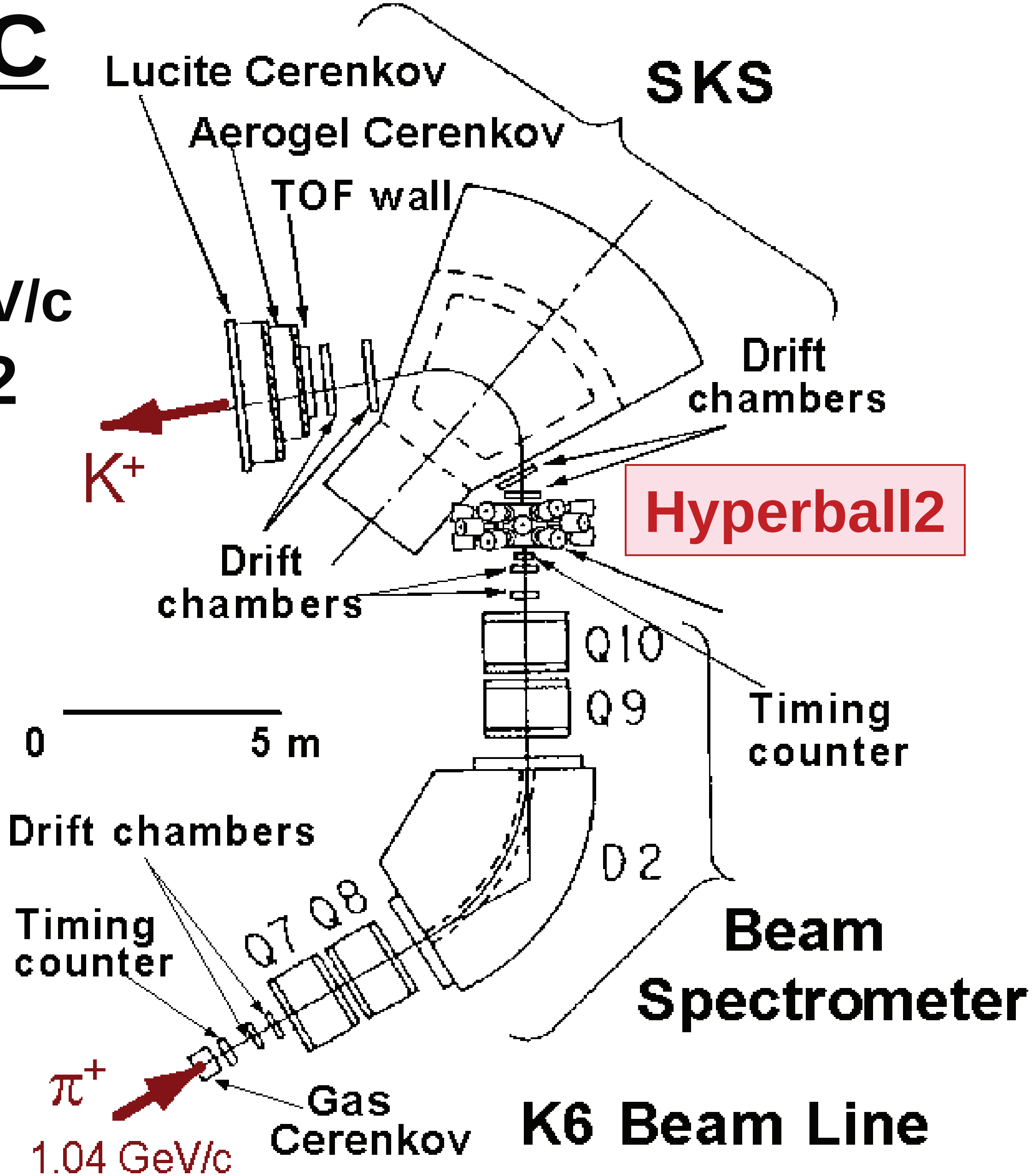
KEK-K6, p_π=1.05 GeV/c
SKS + Hyperball2





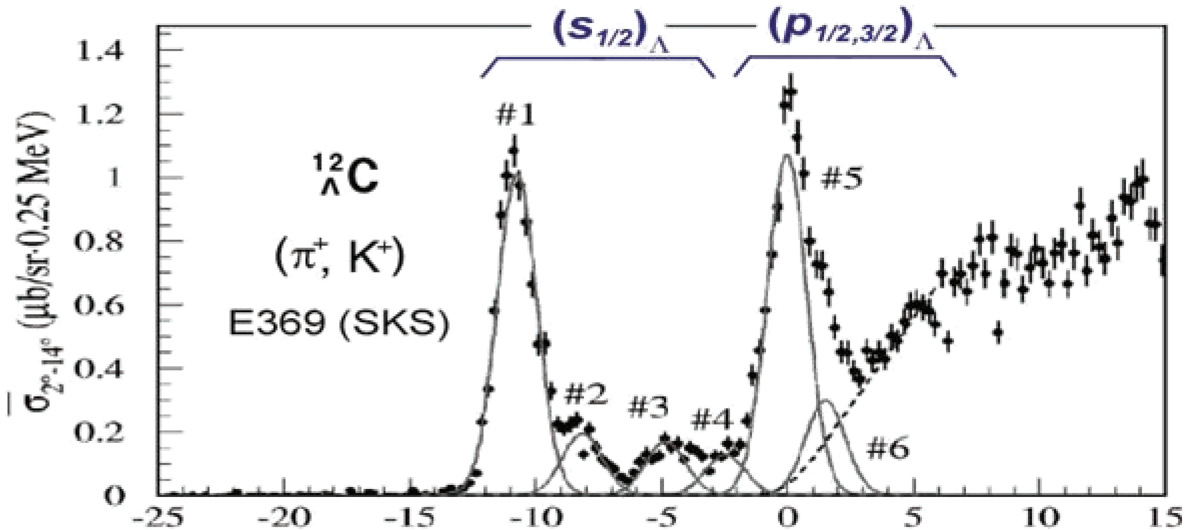
$^{12}C\ (\pi^+,K^+)\ ^{12}{}_{\Lambda}C$ (KEK E566)

KEK-K6, p_π=1.05 GeV/c
SKS + Hyperball2

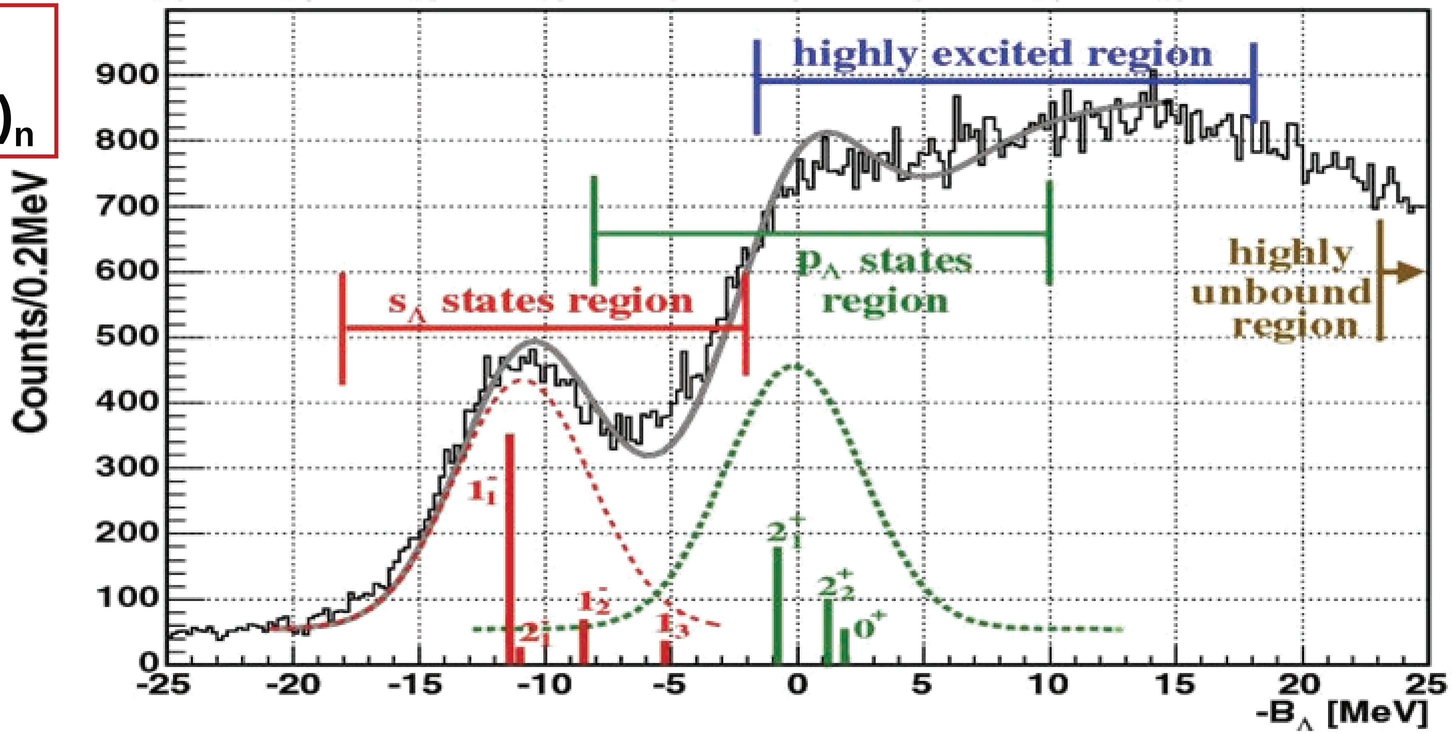


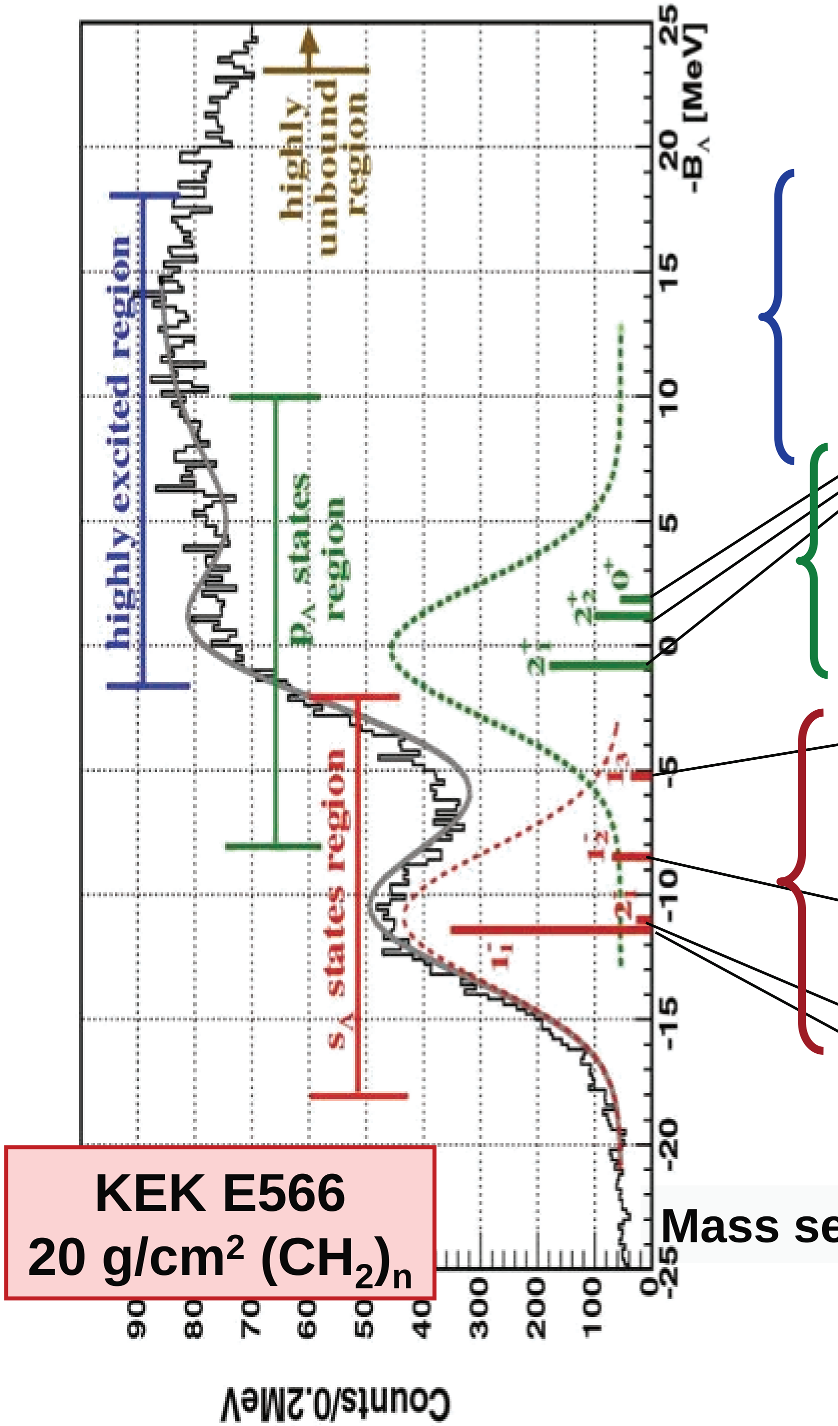
$^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$ mass spectra

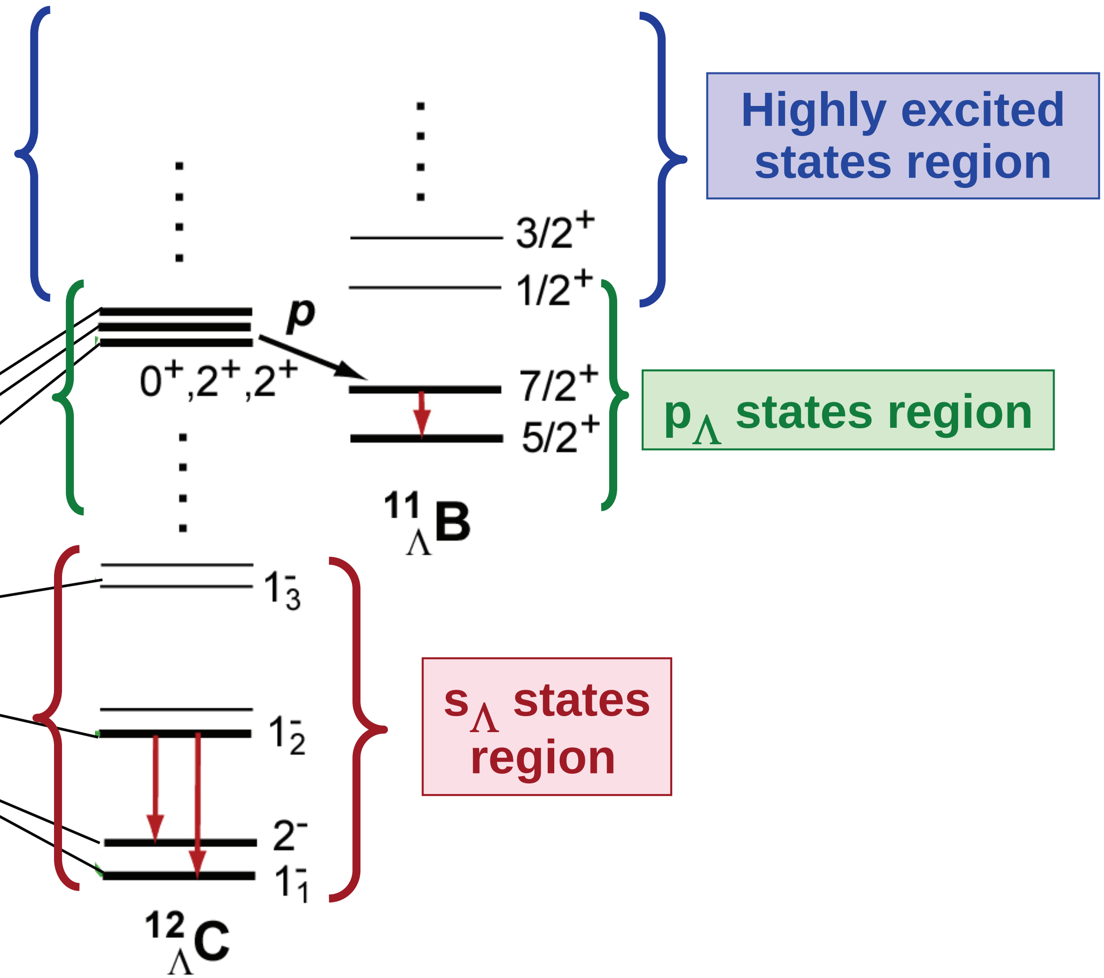
KEK E369
1.7 g/cm² C



KEK E566
20 g/cm² $(CH_2)_n$

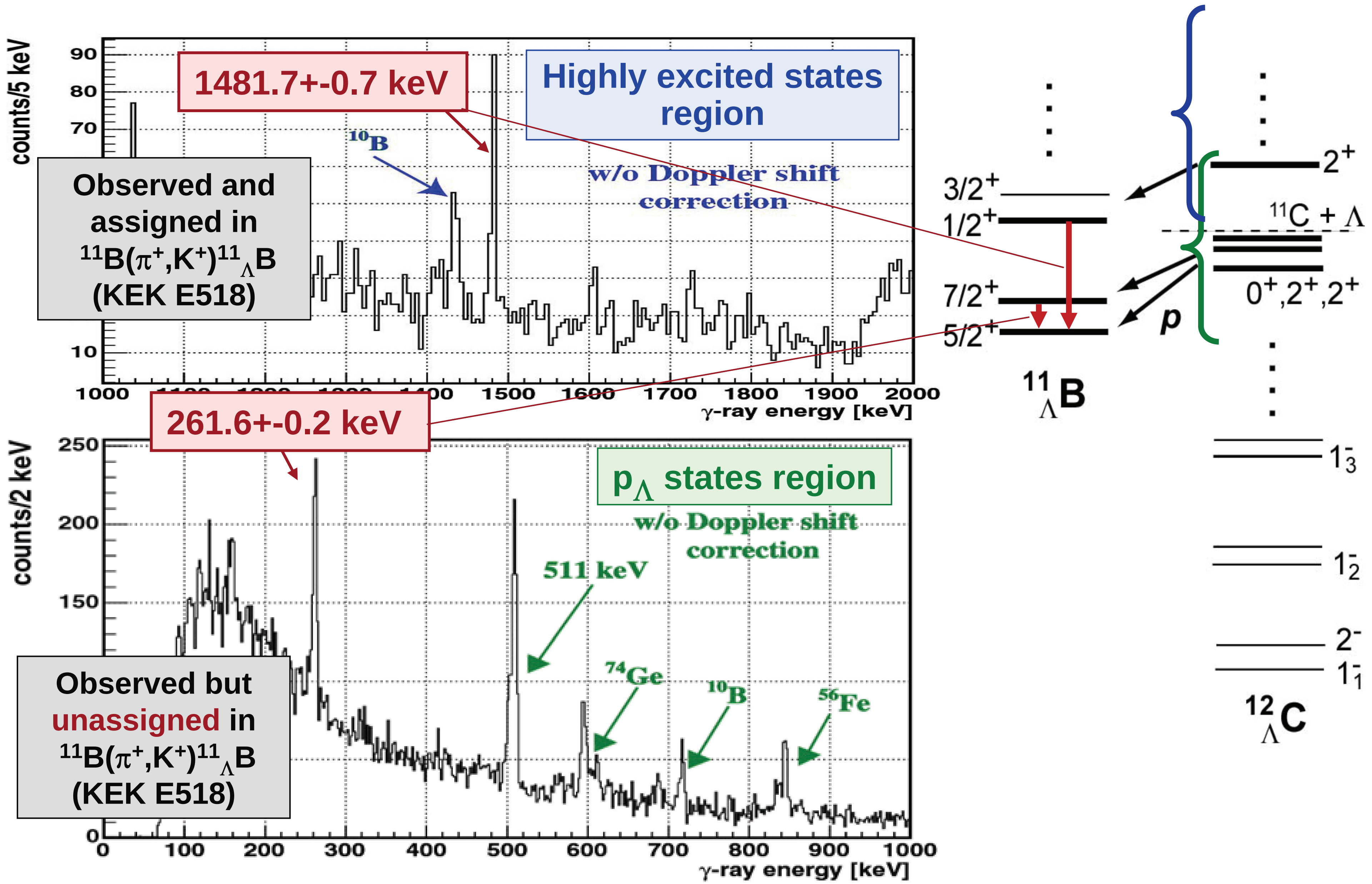




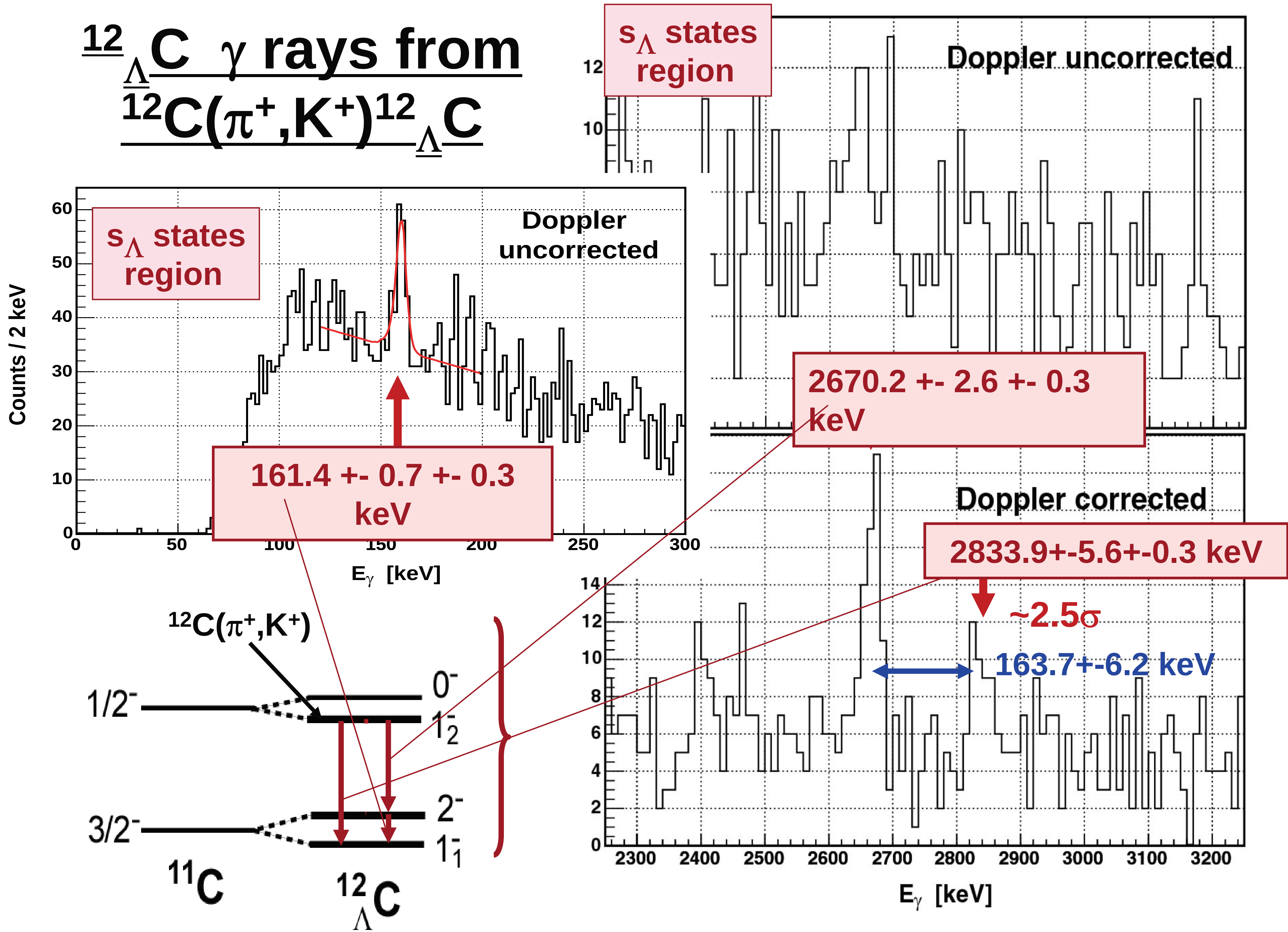


Mass selection

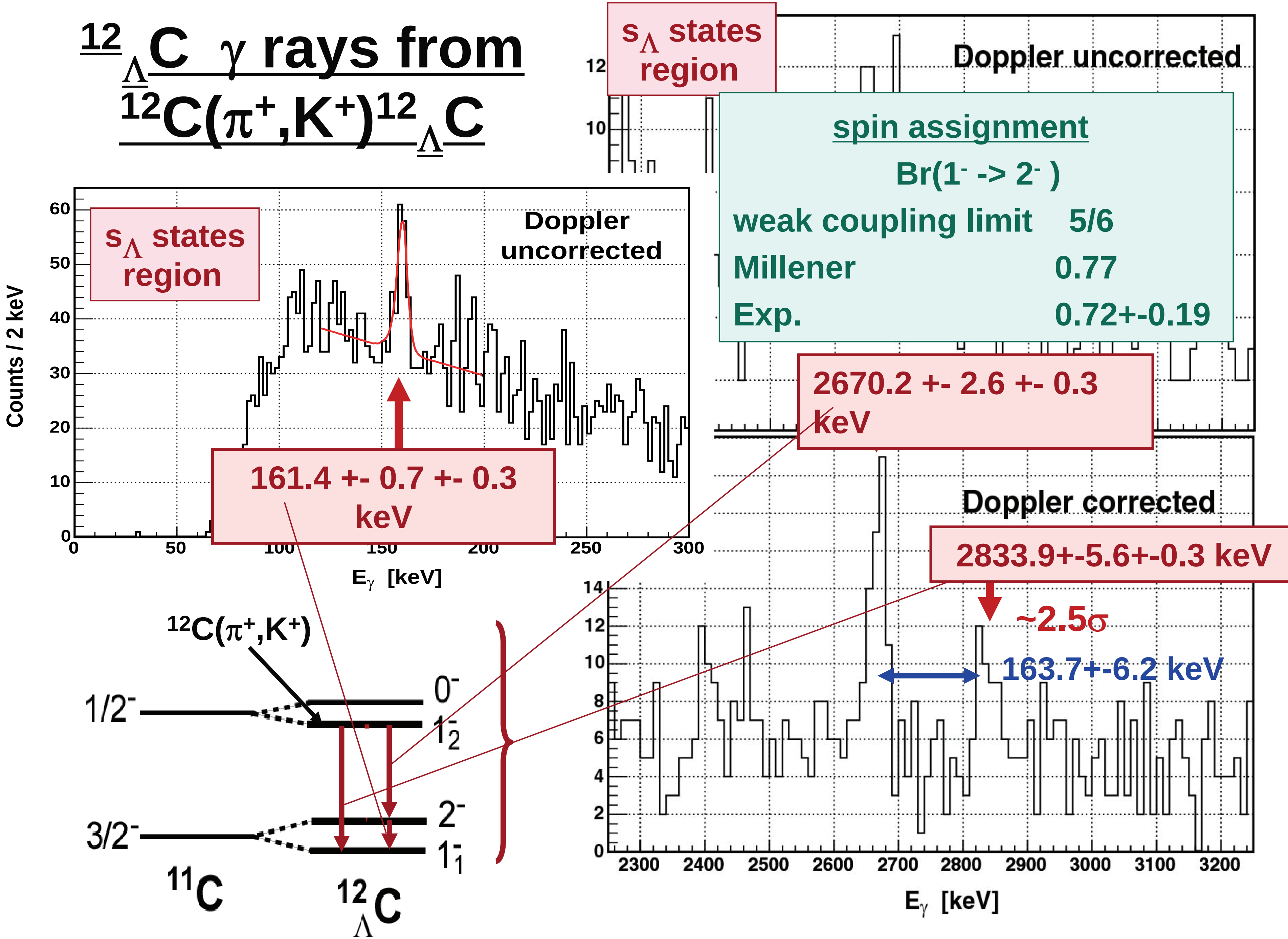
$^{11}{}_{\Lambda}B$ γ rays from $^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$



$^{12}_{\Lambda}C$ γ rays from $^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$



${}^{12}_{\Lambda}C$ γ rays from ${}^{12}C(\pi^+,K^+){}^{12}_{\Lambda}C$



3.3 ΛN interaction

ΛN Spin-dependent interactions

- **Two-body ΛN effective interaction**

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

$\bar{V}$ Δ S_Λ S_N T

Millener's approach

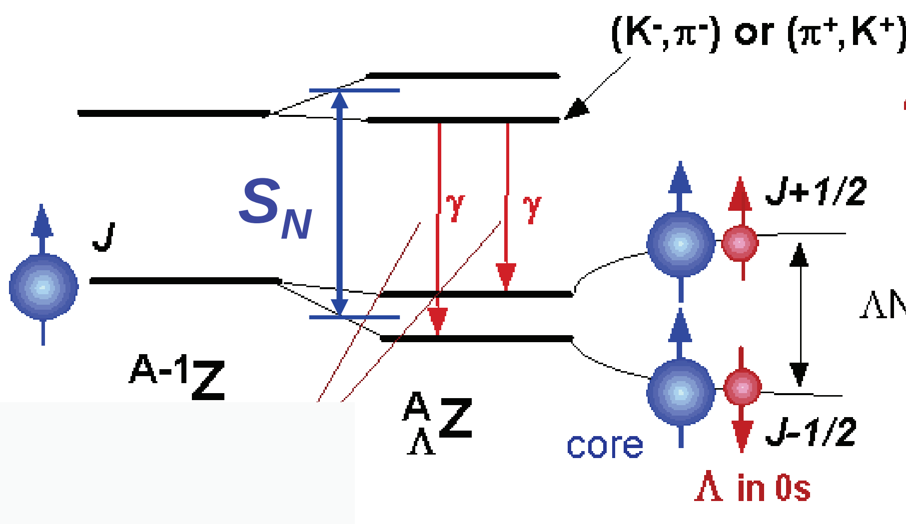
Well know from U_Λ = - 30 MeV

p-shell: 5 radial integrals for $p_\Lambda s_\Lambda$ w.f.

$$\Delta = \int V_\sigma(r)\,|u(r)|^2 r^2 dr, \quad \mathbf{r} = \mathbf{r}_{s_\Lambda} - \mathbf{r}_{p_N}$$

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

Level spacing: linear combination of Δ, S_Λ, S_N, T

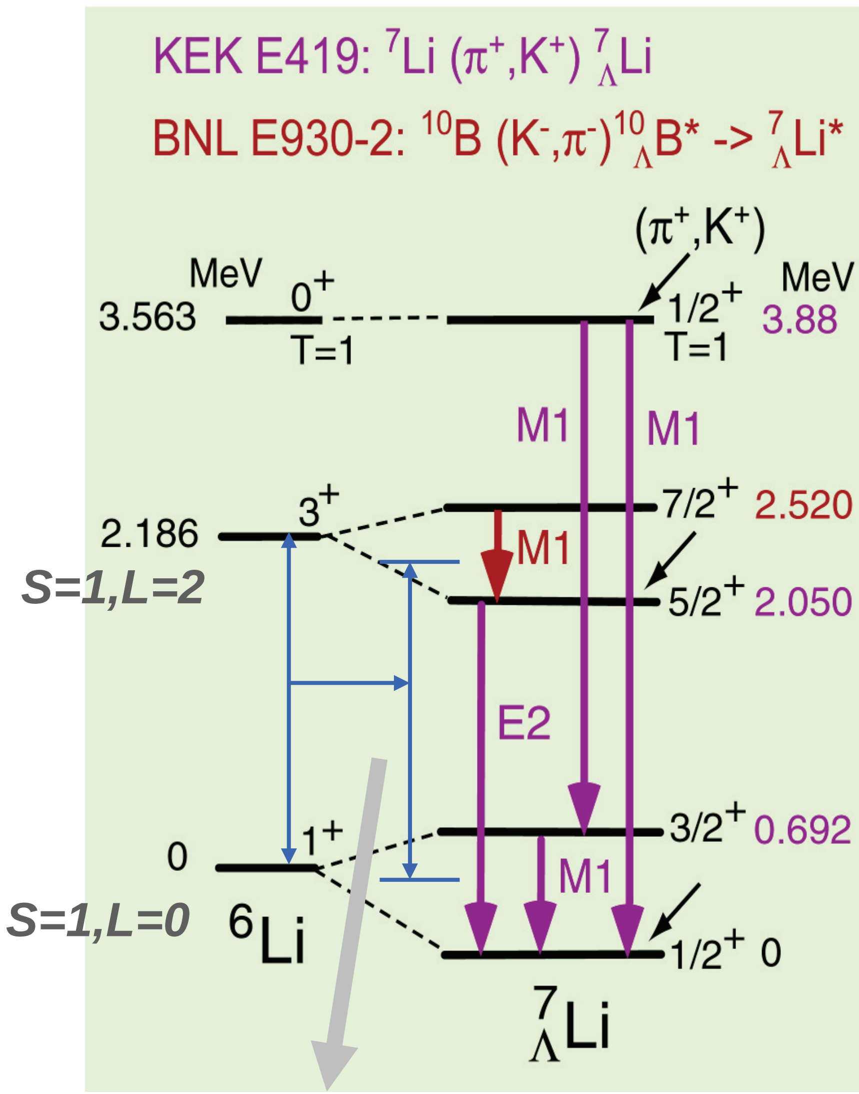


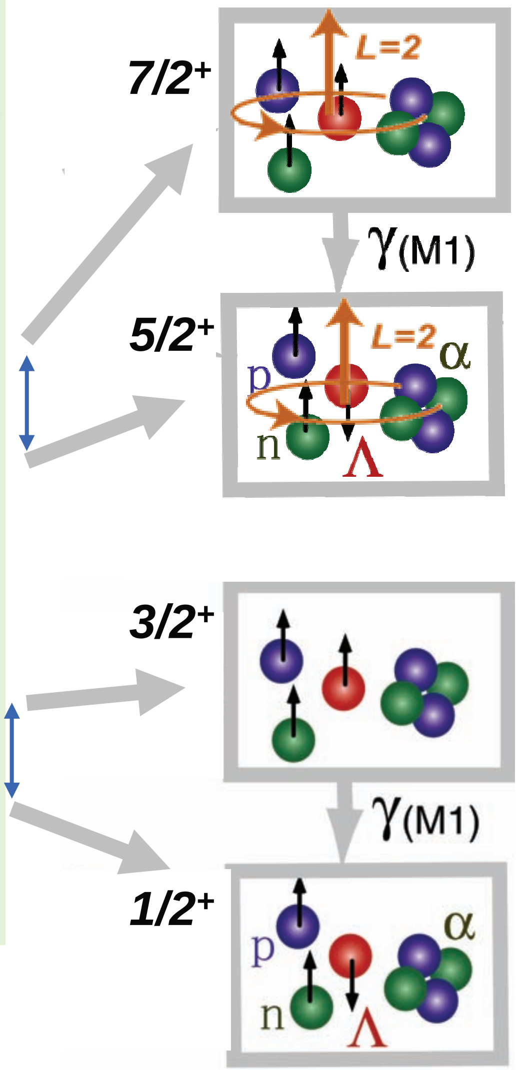
"Hypernuclear Fine Structure"

split by
ΛN spin-dependent
interactions
≲ 0.1 MeV

Δ, S_Λ, T

ΛN interaction from $^{7}_{\Lambda}Li$





spin-spin + LS_Λ interaction

$\Delta E = 1.29\Delta + 2.17S_\Lambda - 2.38T$

$\to \Delta = 0.43$ MeV

$S_\Lambda \sim -0.01$ MeV

spin-spin interaction

$\Delta E = 1.44\,\Delta + 0.05S_\Lambda - 0.27T$

$\to \Delta = 0.43$ MeV

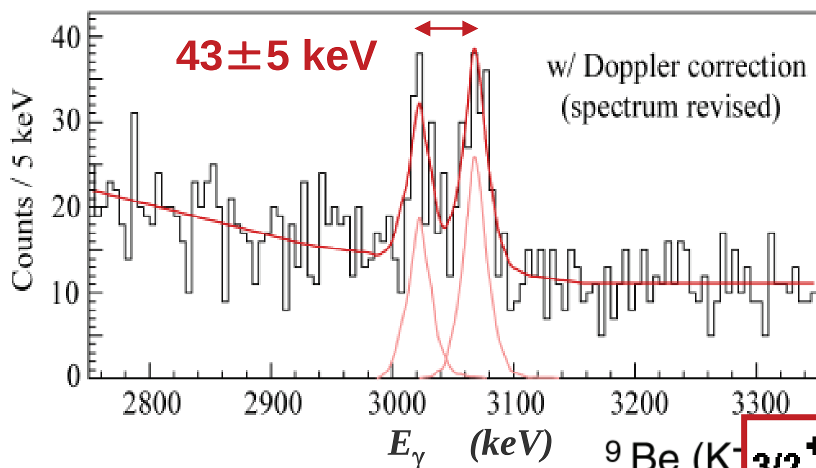
LS_N interaction

$\Delta E = 0.70S_N \quad \to \quad S_N \sim -0.4$ MeV

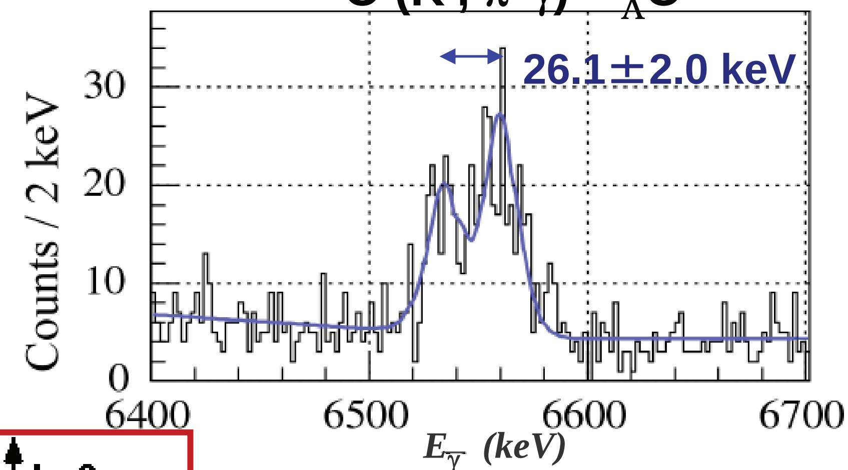
Observation of “Hypernuclear Fine Structure”

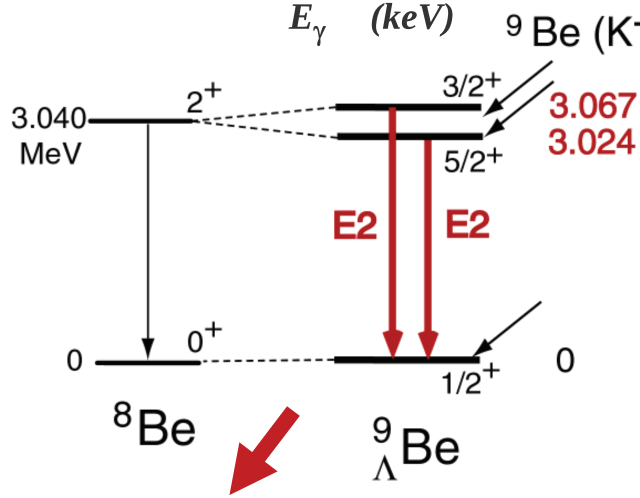
BNL E930 (AGS D6 line + Hyperball)

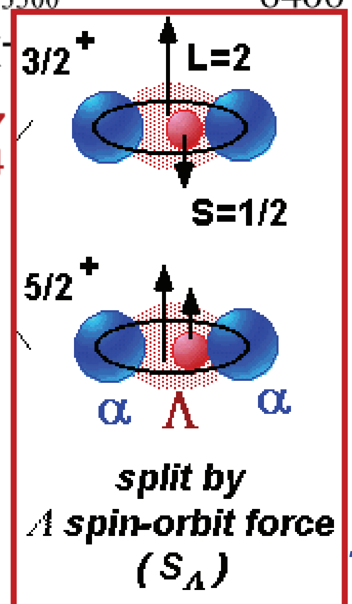
^{9}Be (K$^-$, π^- γ) $^{9}_{\Lambda}$Be

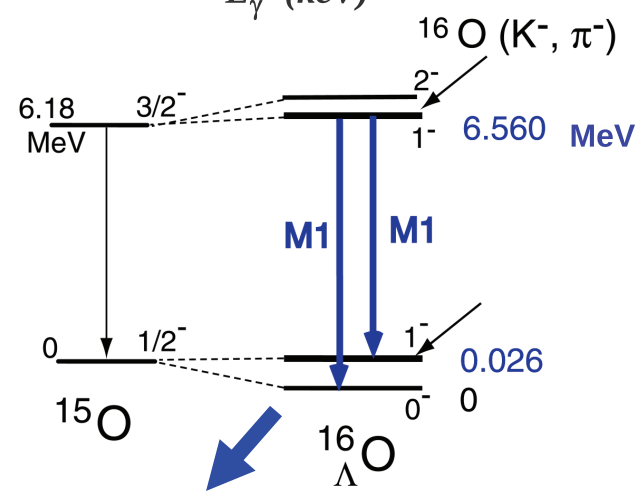


^{16}O (K$^-$, π^- γ) $^{16}_{\Lambda}$O







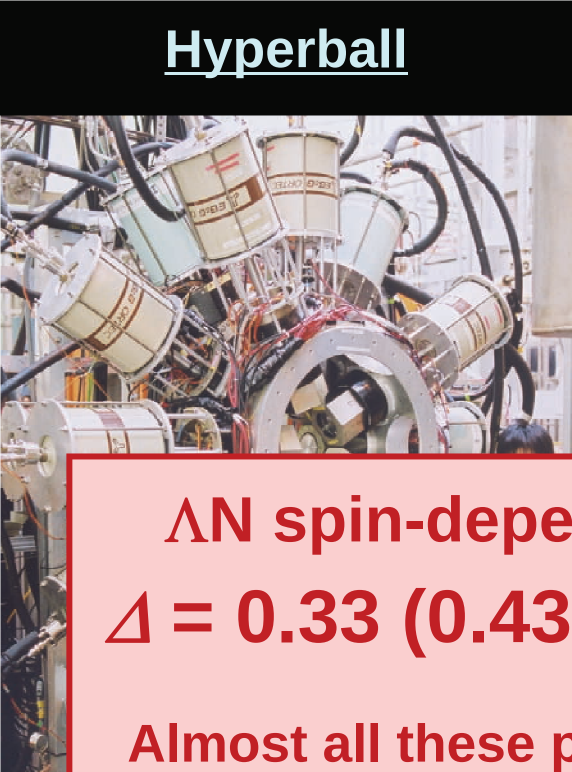


S_{Λ} = -0.01 MeV

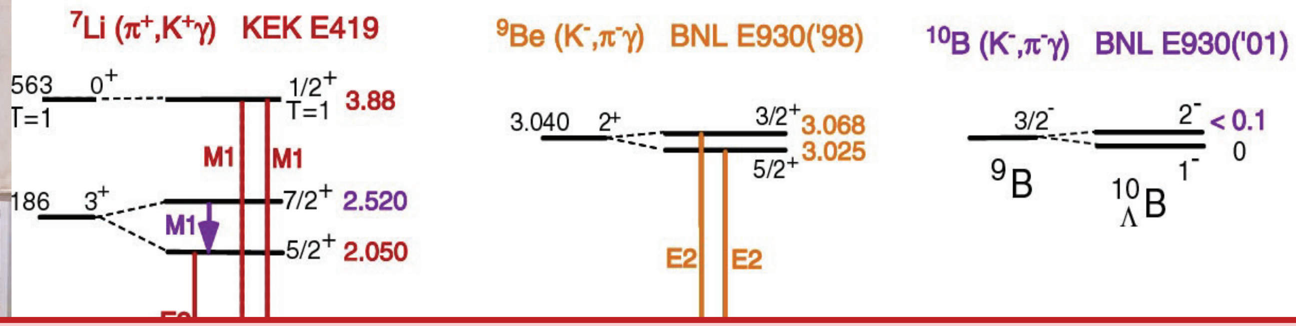
T = 0.03 MeV

PRL 88 (’02) 082501

PRL 93 (2004) 232501



Hypernuclear γ-ray data

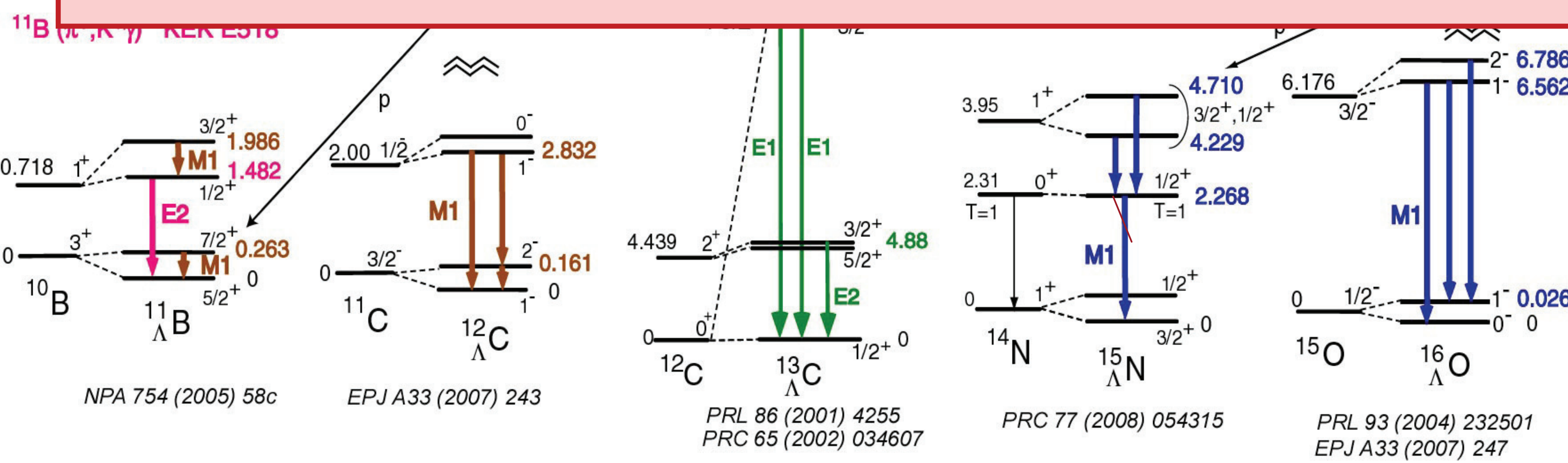


ΛN spin-dependent interaction strengths determined:

$$\Delta = 0.33\ (0.43),\quad S_{\Lambda} = -0.01,\quad S_N = -0.4,\quad T = 0.03\ \text{MeV}$$

Almost all these p-shell levels are reproduced by this parameter set.

(D.J. Millener)



Feedback to BB interaction models

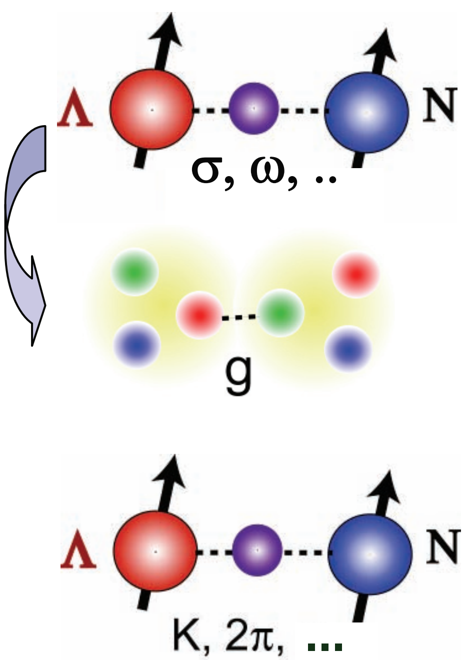
Nijmegen meson-exchange models

	Δ	S_Λ	S_N	T (MeV)
ND	-0.048	-0.131	-0.264	0.018
NF	0.072	-0.175	-0.266	0.033
NSC89	1.052	-0.173	-0.292	0.036
NSC97f	0.754	-0.140	-0.257	0.054
("Quark"		0.0	-0.4	)
Exp.	**0.3~0.4**	**-0.01**	**-0.4**	**0.03**

ND, NF, NSC89, NSC97f: G-matrix calc. by Yamamoto

"Quark": Strength equivalent to quark-model LS force by Fujiwara et al.

Hiyama et al., PRL 85 (2000) 270
Fujiwara et al. Prog.Part.Nucl.Phys.58 (2007) 439.



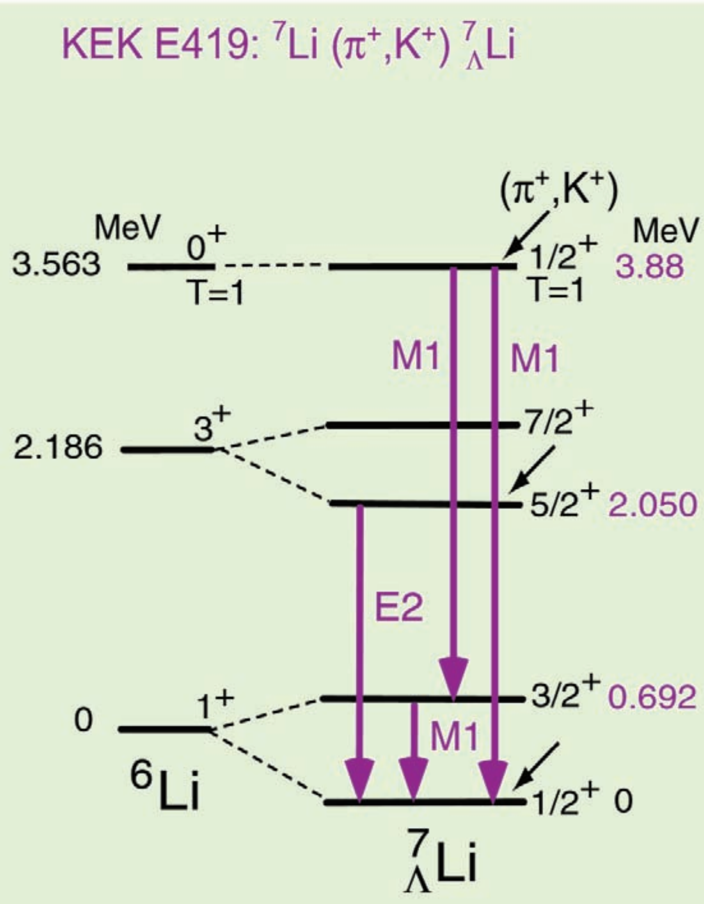
Origin of the ΛN spin-orbit force:
Quark-gluon exchange
rather than heavy meson exchange ?

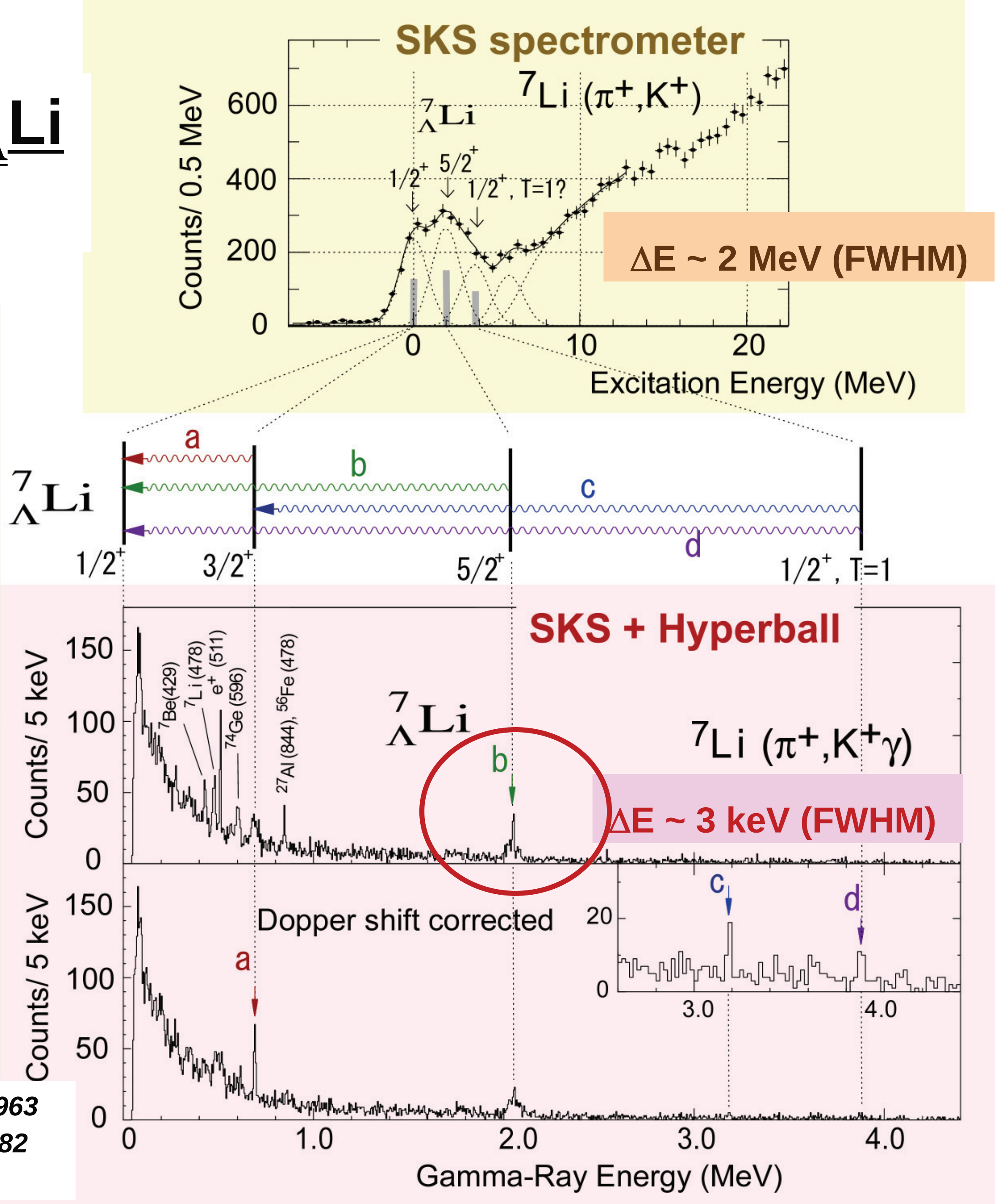
=> Nijmegen interaction updated to include it (ESC06)

Origin of ΛN tensor force:
Meson exchange. Same as NN tensor force

3.4 Impurity effect

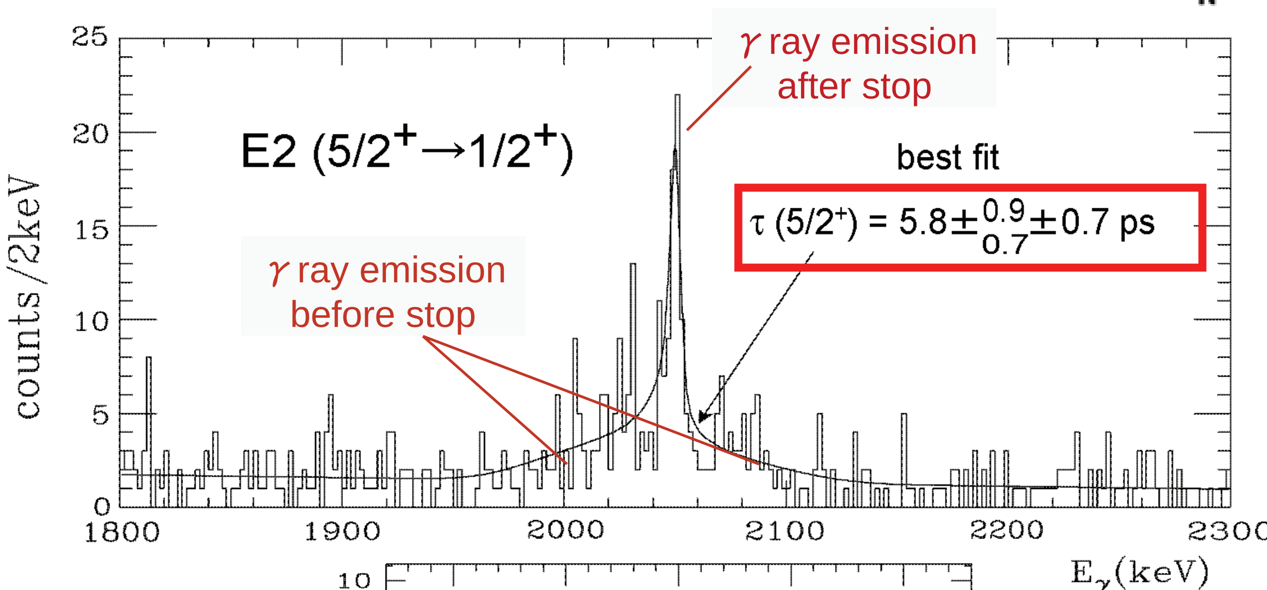
γ-ray spectrum of ${}^{7}_{\Lambda}$Li
(KEK E419)

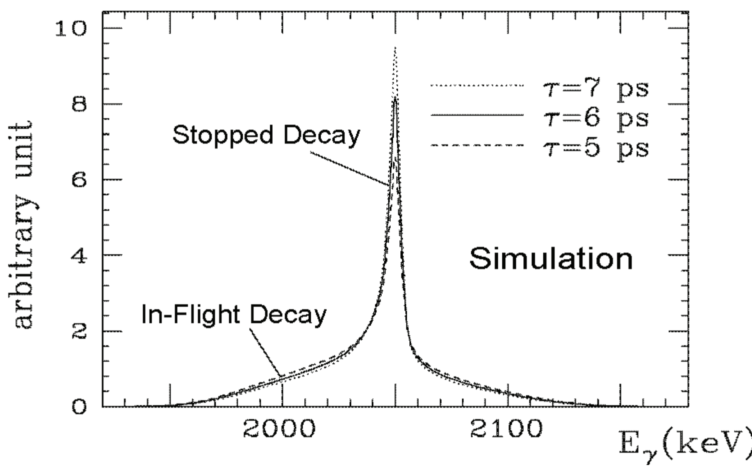


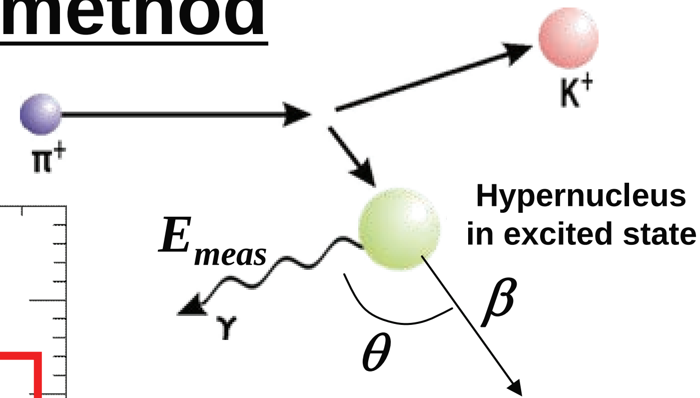


H. Tamura et al., Phys. Rev. Lett. 84 (2000) 5963
K. Tanida et al., Phys. Rev. Lett. 86 (2001) 1982
J. Sasao et al., Phys. Lett. B 579 (2004) 258

Lifetime measurement by Doppler shift attenuation method



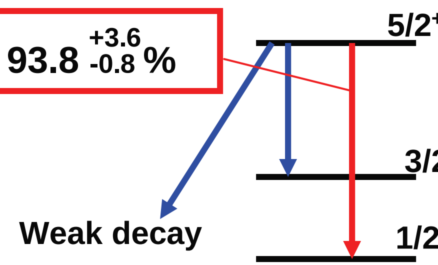




Doppler shift

$$E_{meas} \cong E_0(1+\beta\cos\theta)$$

Br = 93.8 $^{+3.6}_{-0.8}$ %

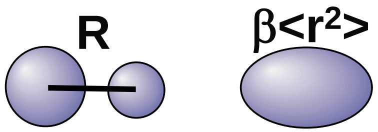


$$\Gamma_\gamma = Br / \tau = (4\pi/75\hbar)\,(E_\gamma/\hbar c)^5\ B(E2)$$

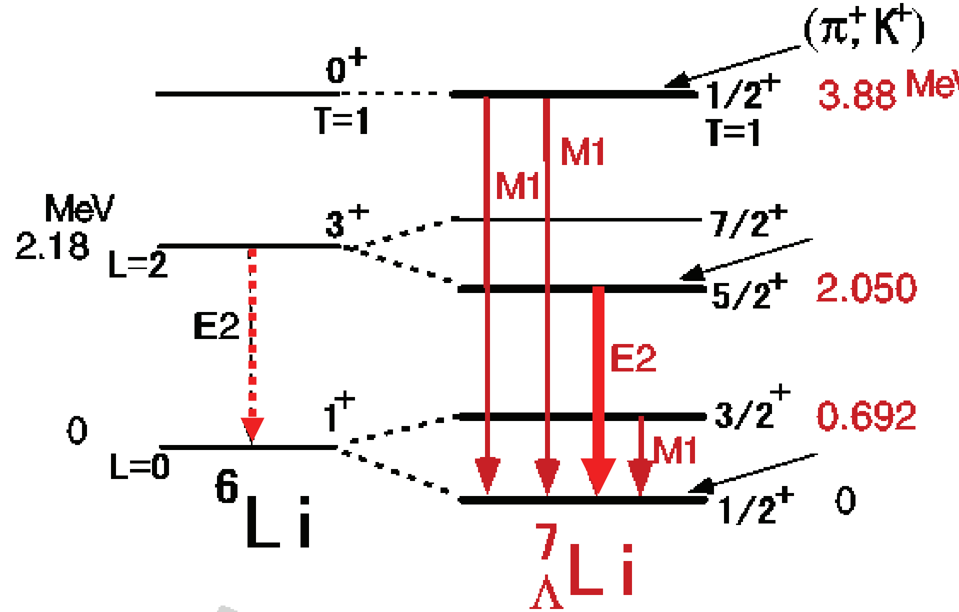
$$= 1.22\times10^9\ E_{\gamma\,[MeV]}^5\ B(E2)_{[e^2fm^4]}$$

B(E2) = 3.6 ± 0.5 $^{+0.5}_{-0.4}$ e^2fm^4

Hypernuclear Shrinking effect

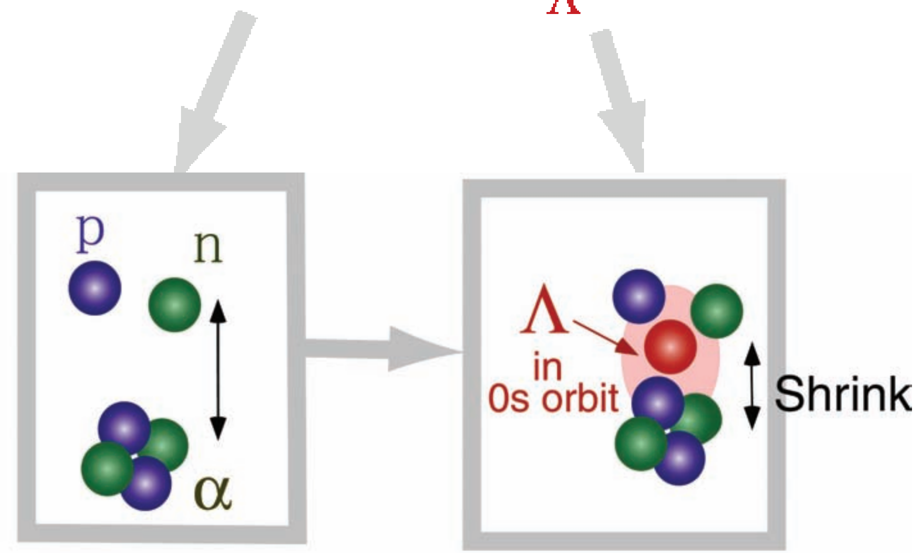


$B(E2) \propto |\langle f|\, e\, r^2 Y_2\, |i\rangle|^2$
$\propto R^4$ or $(\beta\langle r^2\rangle)^2$



Predicted by Motoba, Bando, Ikeda
Prog.Theor.Phys. 70 (1983) 189.

^{4}He + d + Λ model ~20% shrinkage
Λ in 0s attracts nucleons "Glue role of Λ"



B(E2) 10.9±0.9 → 3.6±0.5$^{+0.5}_{-0.4}$
e^2fm^4
⇒ 19±4% Shrinkage by Λ

Hiyama et al.
PRC 59 (1999) 2351, NPA684(2001)227
$^5_\Lambda$He + p + n, ^{4}He + p + n + Λ
Shrink between $^5_\Lambda$He – pn distance
22% shrinkage

Tanida et al., PRL 86 (2001) 1982

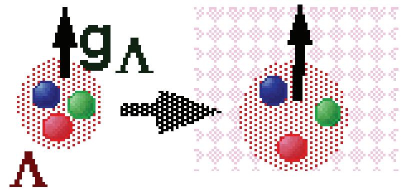
3.5 Medium effect of baryons

Magnetic moment of a Λ in a nucleus

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

Baryon magnetic moment in nucleus:
affected by partial restoration of chiral symmetry?
→ Origin of baryon spin and mass
Λ free from Pauli effect is a good probe.

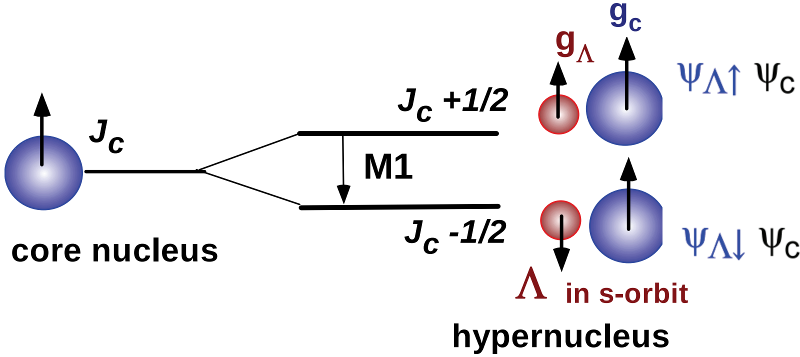
decrease m_q → increase μ_q ?



swelling → increase μ_q ?

- **Direct measurement is difficult (τ ~ 0.1-- 0.2 ns)**
- **Λ-spin-flip M1 transition: B(M1) -> g_Λ**

$$B(M1) = (2J_{up}+1)^{-1} \left| \langle \Psi_{low} \| \mu \| \Psi_{up} \rangle \right|^2$$
$$= (2J_{up}+1)^{-1} \left| \langle \psi_{\Lambda\downarrow} \psi_c \| \mu \| \psi_{\Lambda\uparrow} \psi_c \rangle \right|^2$$
$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$$



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

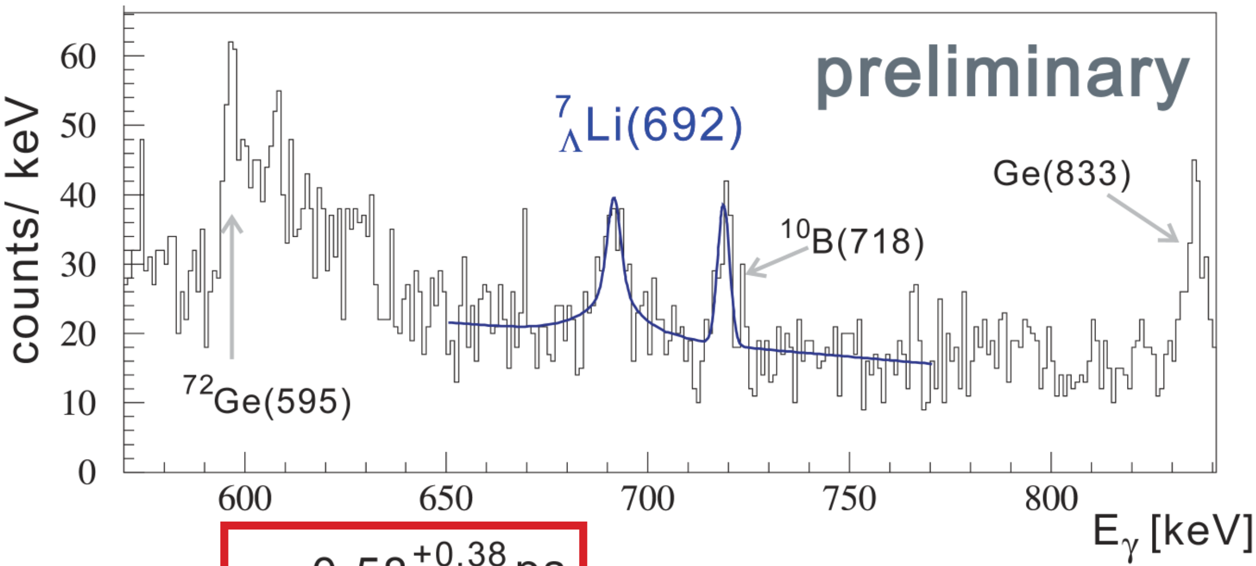
~100% **Doppler Shift Attenuation Method :**

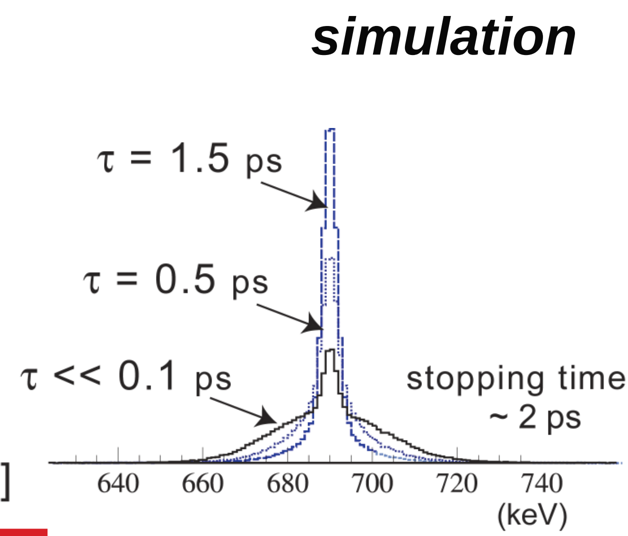
$$\Gamma = BR/\tau = \frac{16\pi}{9} E_\gamma^3 \, B(M1)$$

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





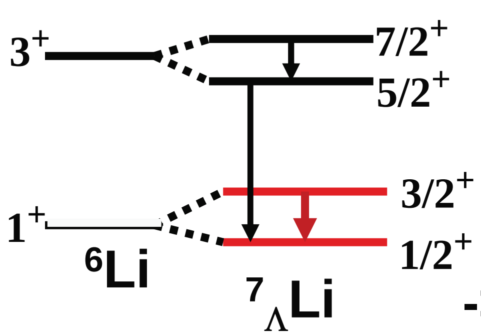
$\tau = 0.58^{+0.38}_{-0.20}$ ps

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)



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

First data of g_{Λ} in nucleus

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

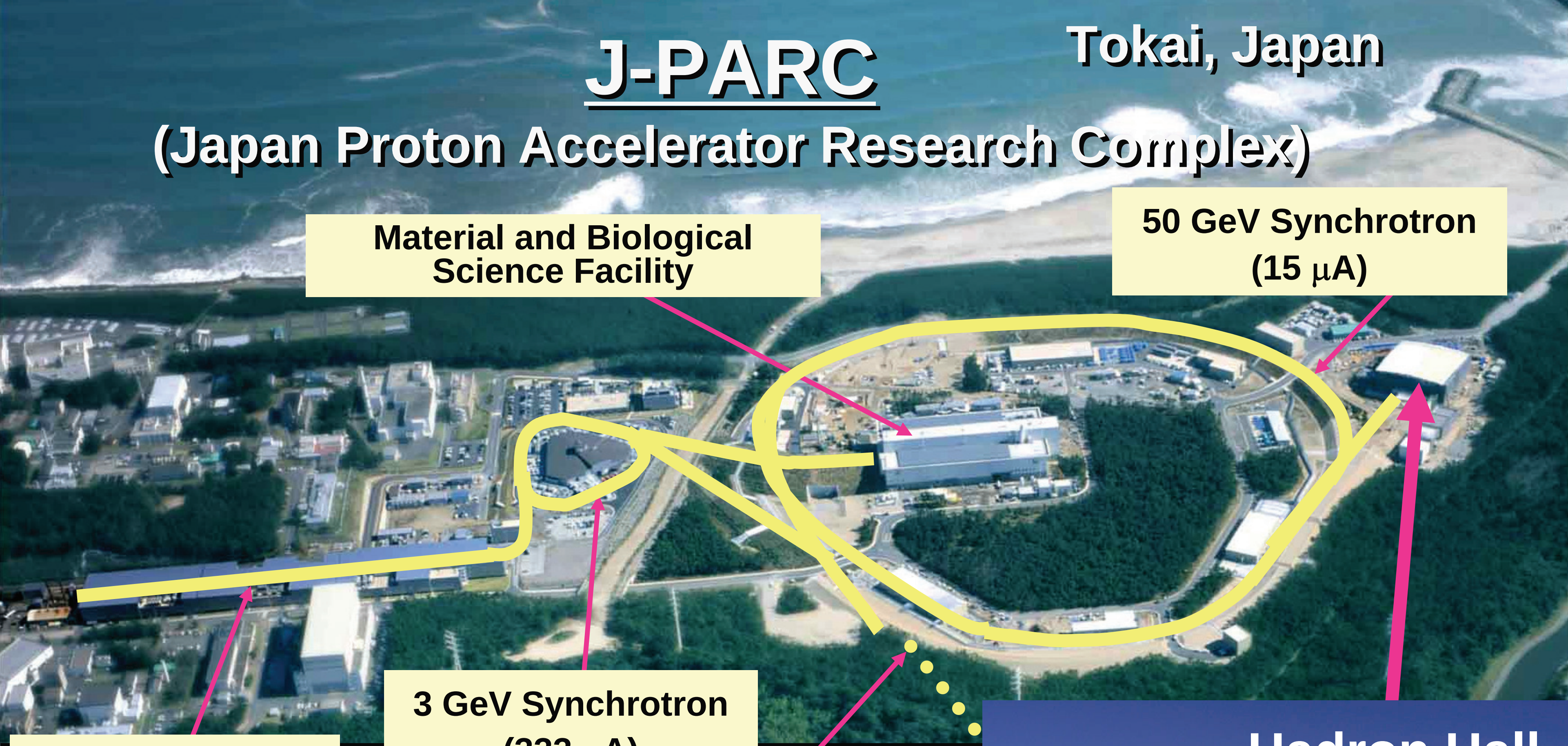
J-PARC E13

4. Experiments at J-PARC

J-PARC

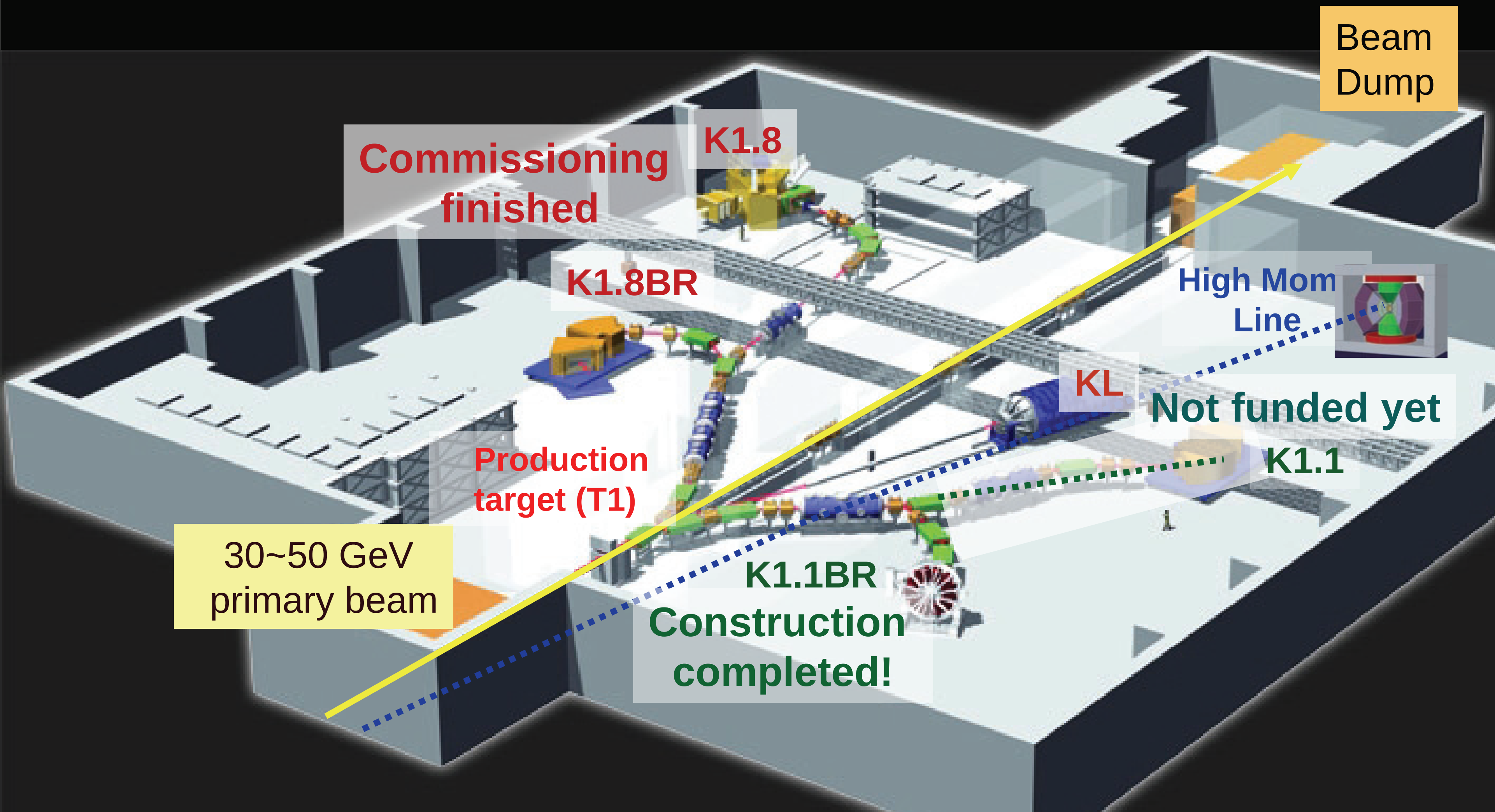
(Japan Proton Accelerator Research Complex)

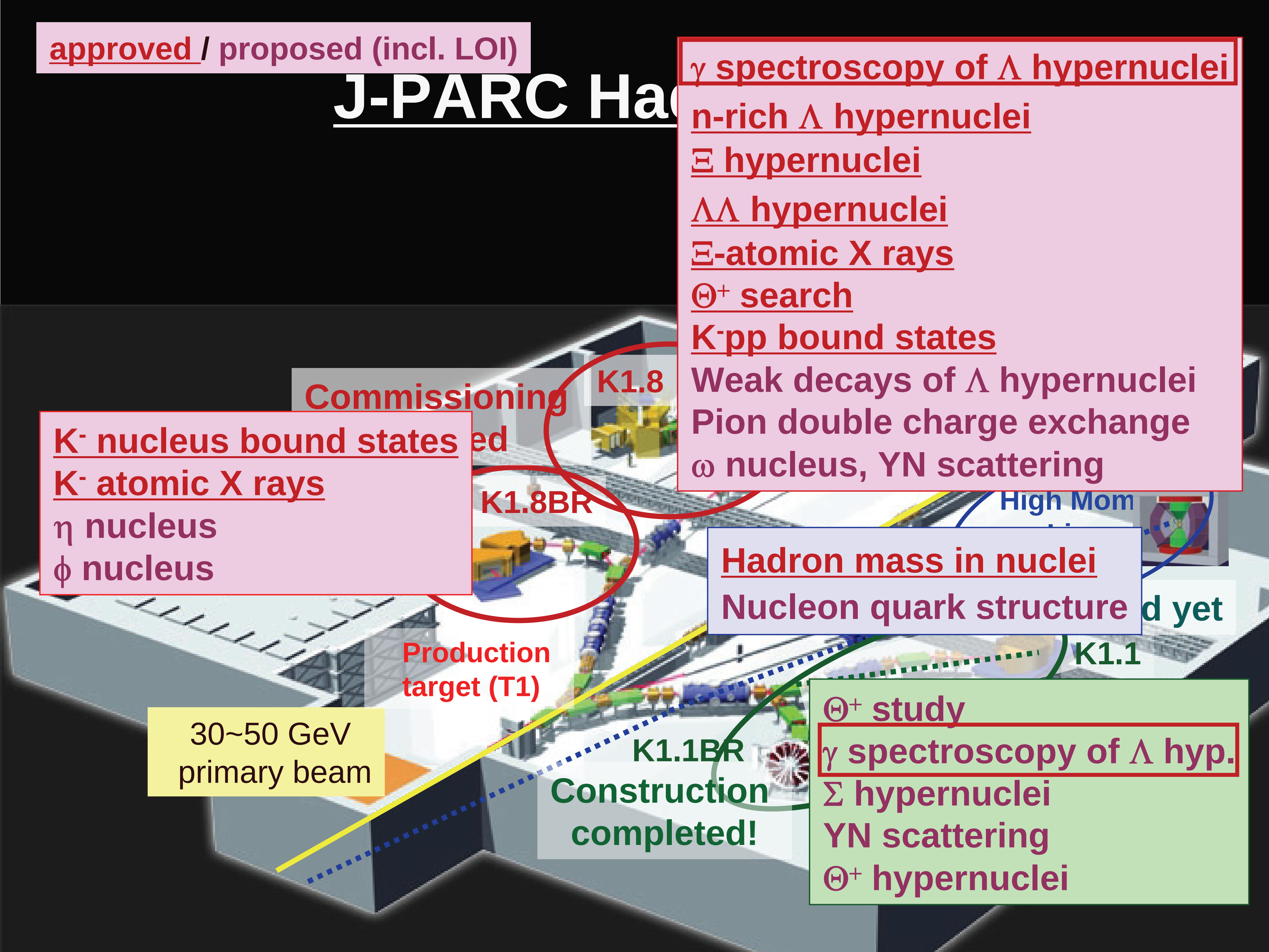
Tokai, Japan



World-highest beam intensity :
~ 1 MW
x10 of BNL-AGS, x100 of KEK-PS

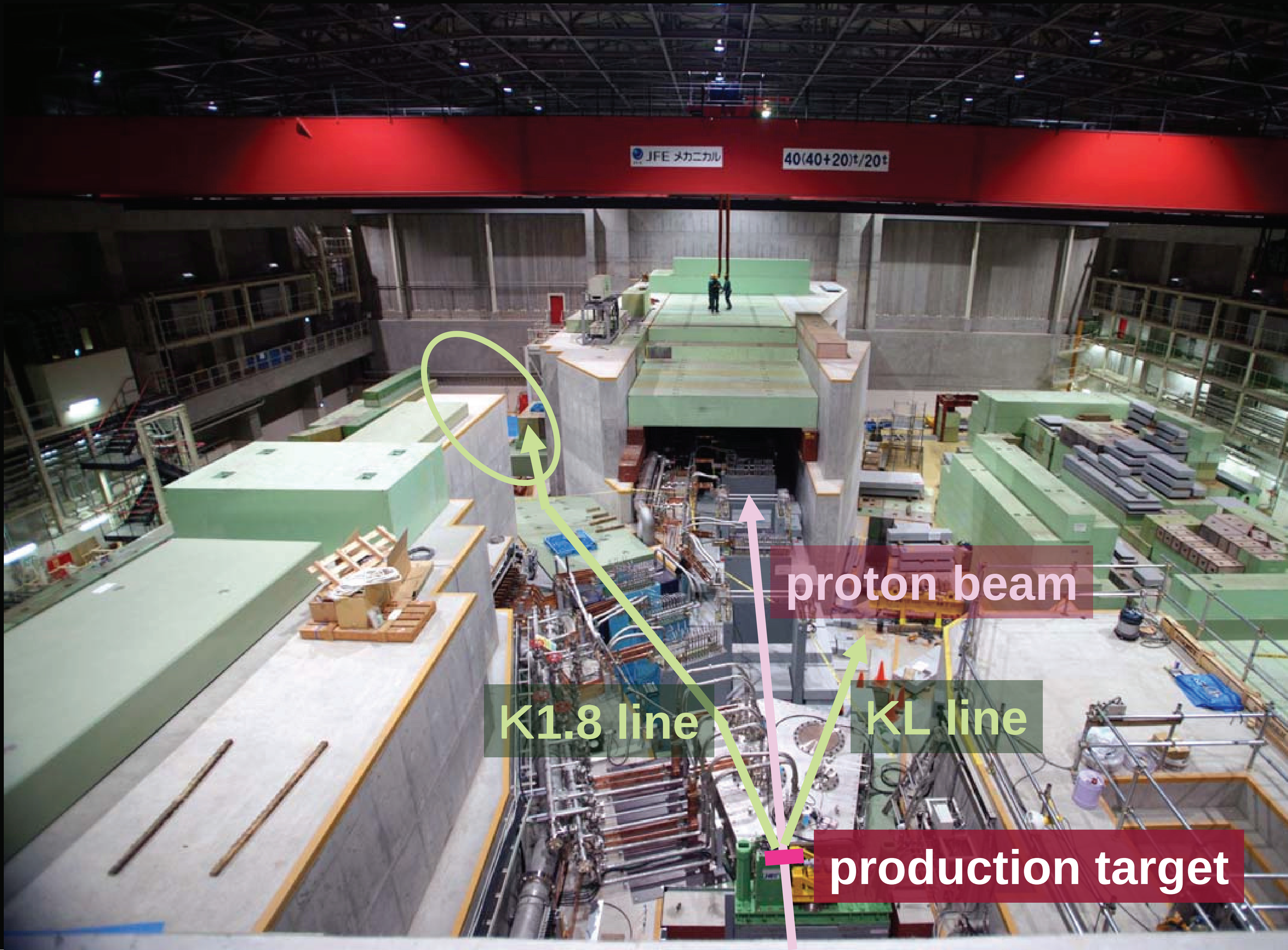
J-PARC Hadron Hall





approved / proposed (incl. LOI)
J-PARC Ha
γ spectroscopy of Λ hypernuclei
n-rich Λ hypernuclei
Ξ hypernuclei
ΛΛ hypernuclei
Ξ-atomic X rays
Θ+ search
K-pp bound states
Weak decays of Λ hypernuclei
Pion double charge exchange
ω nucleus, YN scattering
K1.8
Commissioning
K- nucleus bound states
K- atomic X rays
η nucleus
ϕ nucleus
K1.8BR
High Mom
Hadron mass in nuclei
Nucleon quark structure
d yet
K1.1
Production target (T1)
30~50 GeV primary beam
K1.1BR
Construction completed!
Θ+ study
γ spectroscopy of Λ hyp.
Σ hypernuclei
YN scattering
Θ+ hypernuclei

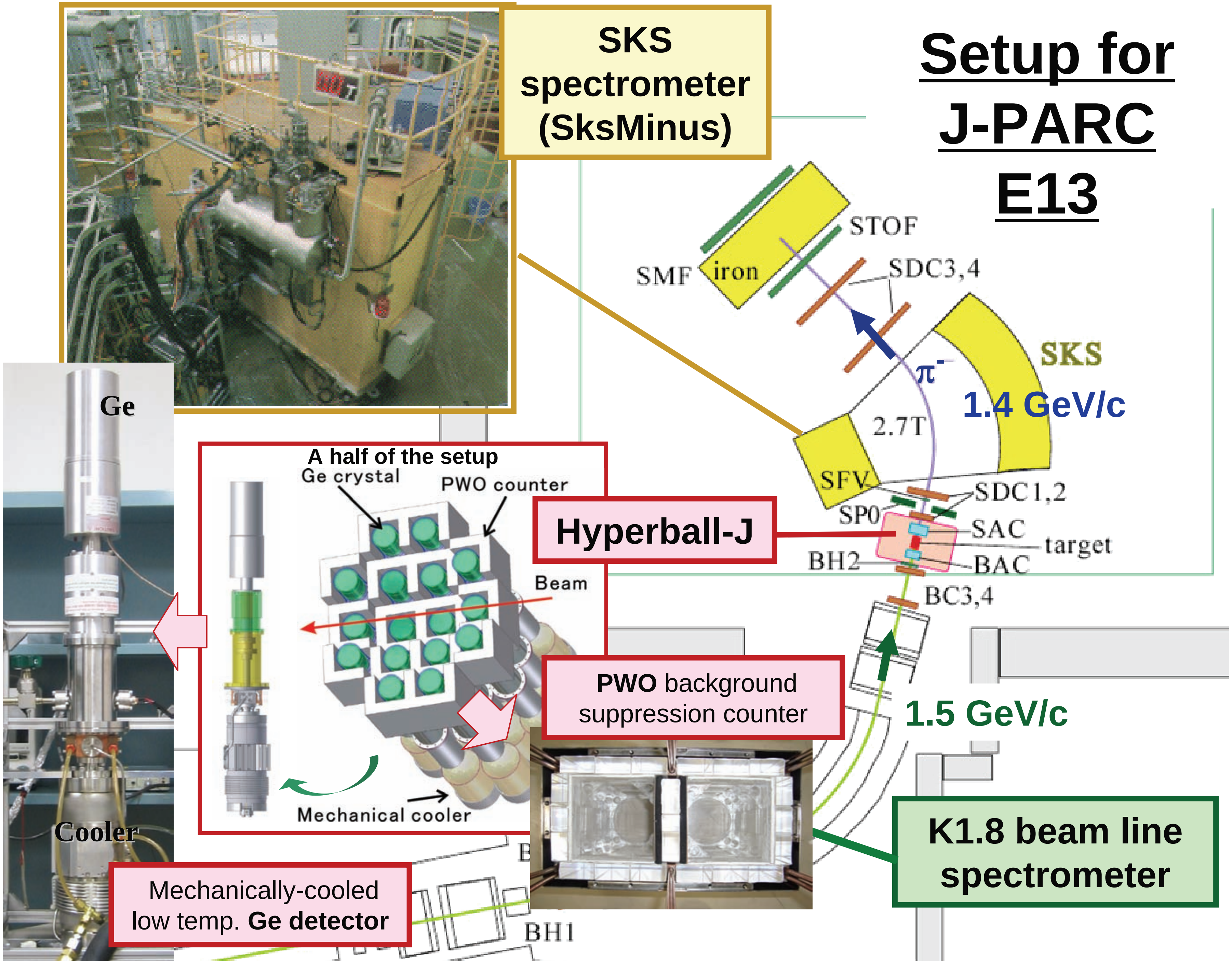
Hadron Hall as of 2008.10



Hadron Hall as of 2008.10

Commissioning finished!

Setup for J-PARC E13



γ spectroscopy at J-PARC

J-PARC E13 + α

- B(M1) measurement of $^{7}_{\Lambda}$Li
- Charge symmetry breaking (pΛ = nΛ?) $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He
- $\Lambda\Sigma$ coupling and ΛNN force $^{10}_{\Lambda}$B, $^{11}_{\Lambda}$B,…
- Radial dependence of ΛN interaction $^{19}_{\Lambda}$F

- Heavy hypernuclei for E1($p_{1/2}^{\Lambda}$, $p_{3/2}^{\Lambda}$ -> s^{Λ}) $^{89}_{\Lambda}$Y, $^{208}_{\Lambda}$Pb
- sd-shell: ΛN interactions and impurity effects $^{20}_{\Lambda}$Ne, $^{25}_{\Lambda}$Mg, $^{28}_{\Lambda}$Si…
- Disappearance of n halo B(E2) in $^{7}_{\Lambda}$He
- B(M1) for various hypernuclei $^{12}_{\Lambda}$C and heavier
- ……

10~100 times faster data collection at J-PARC

5. Summary

- **Hypernuclear spectroscopy provides valuable information on YN interactions, impurity effects and medium effect of baryons.**

- **Reaction spectroscopy by (K^-, π^-), (π^+,K^+) and (e,e'K^+) have been successful:**
  - **Different selectivity in populating states**
  - **Resolution improved down to 0.5 MeV(FWHM)**
  - **Λ single particle orbits well studied**

- **γ spectroscopy of Λ hypernuclei:**
  - **Excellent resolution of 0.002 MeV achieved by Hyperball**
  - **Almost all p-shell data accumulated**
  - **Spin-dependent ΛN interaction strengths determined**
  - **Hypernuclear shrinking effect observed**
  - **g_Λ can be studied**

- **Hypernuclear spectroscopy will be extensively studied at J-PARC.**