Gamma-ray spectroscopy of hypernuclei at J-PARC

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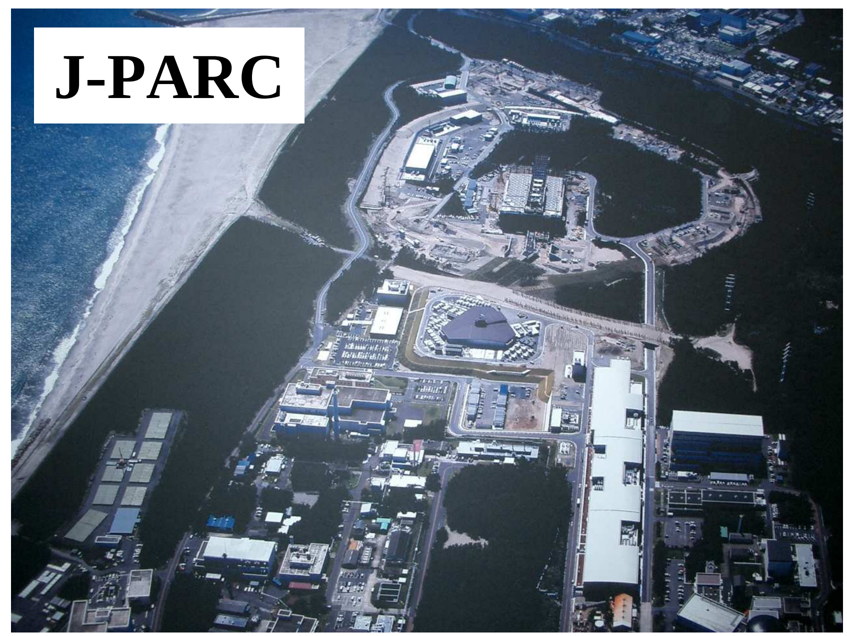
for the Hyperball-J collaboration

Contents

- **Introduction**
  - **ΛN interaction**
  - **Magnetic moment of Λ in nuclear medium**
- **Experimental method**

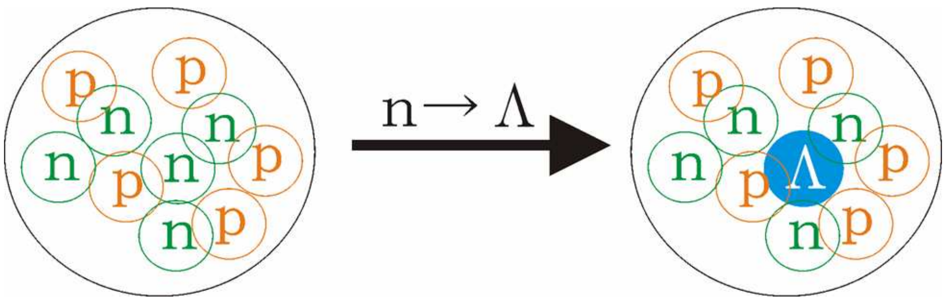


Introduction

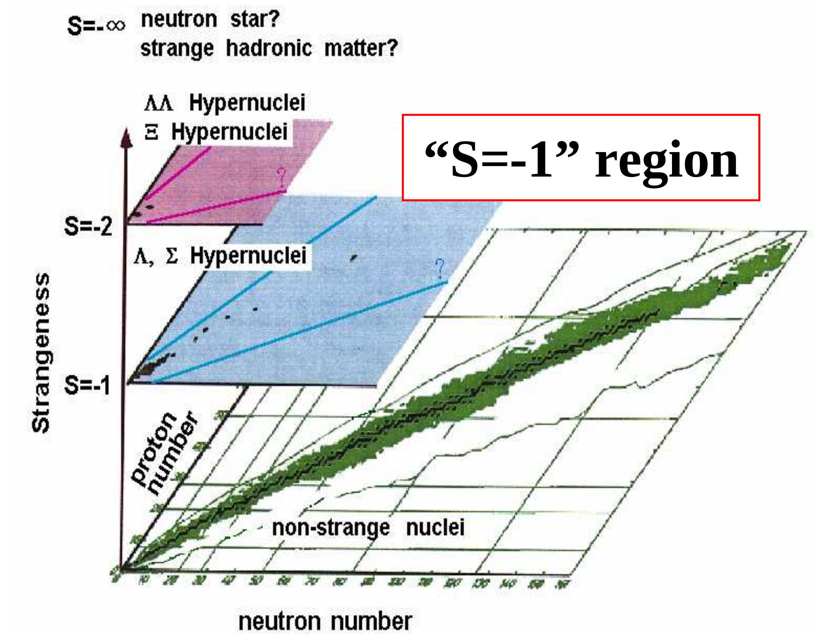
- ΛN interaction
- Magnetic moment of Λ in nuclear medium
- Results of Hyperball experiment

Λ Hypernucleus

Λ hypernucleus → Λ is bound in a nucleus.



Nucleus Λ hypernucleus



N-N interaction → B-B interaction
"Λ-N interaction"

Baryon other than nucleons **(p/n)**

→ Deeply bound in a nucleus w/o Pauli effect →

The possible change of baryon properties in the nuclear medium
"Magnetic moment of Λ"

Basic properties of Λ and production reaction

Decay

- τ_Λ~230 ps (free space)
- $\Lambda \rightarrow p\pi^-$, $n\pi^0$: $\Lambda N \rightarrow NN$ (dominant decay mode in nucleus)

Interaction

- One π exchange forbidden (T_Λ=0, isospin conservation)

➡Weaker interaction

- U_Λ~30 MeV vs U_N~50 MeV

Reaction : (K^-, π^-)

- Secondary beam : Intensity ~10^6 Hz (full intensity at J-PARC)
- Beam momentum : ~1 GeV/c
- Momentum transfer
  - q = 100 MeV/c (0°) : ΔL = 0
  - q = 150-200 MeV/c (10-15°) : ΔL = 1, 2
- Cross section : a few 10~100 μb/sr

Study of Λ-N interaction

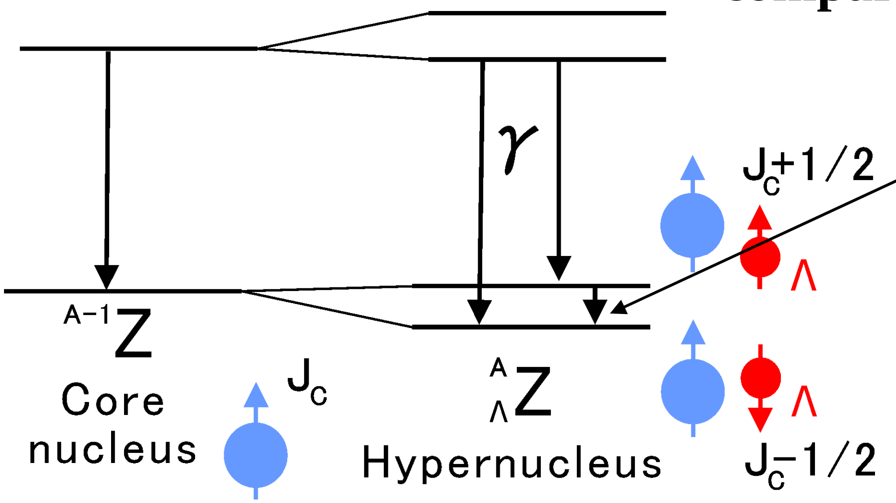
Hyperon-nucleon / Hyperon-hyperon scattering impractical

➡ γ-ray spectroscopy

Experimental result
⇒Level scheme

⟷ compared

Theoretical calculation from free space ΛN interaction model via G-Matrix method



4 spin-dependent interaction

- **Spin-spin**
- **Λ-spin-dependent spin-orbit**
- **Nucleon-spin-dependent spin-orbit**
- **Tensor**

Spin dependent interaction

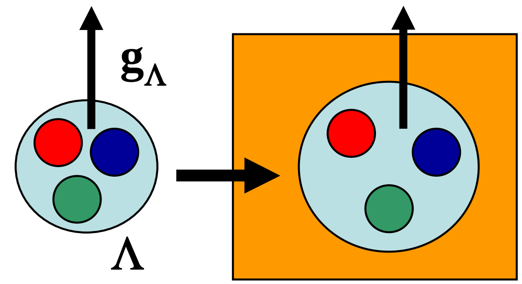
- **Energy spacing of hypernuclei (~ a few 100 keV).**

e.g. 26 keV spacing @ $^{16}_{\Lambda}O$

➡ Only γ-ray spectroscopy with germanium detectors (2-3keV)

Magnetic moment of Λ in nuclear medium

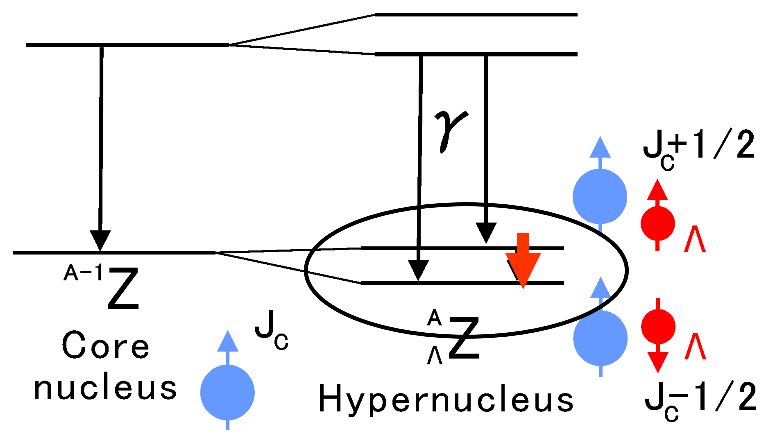
➢ μ_Λ in nucleus
→ Medium effect of baryons



Swelling?
Mass reduction ?

Partial restoration of chiral symmetry
Reduction of constitute quark mass ?
Swelling?

μ_Λ in nucleus is extracted from Λ-spin-flip B(M1) transition measurement.
(Direct measurement is extremely difficult.)

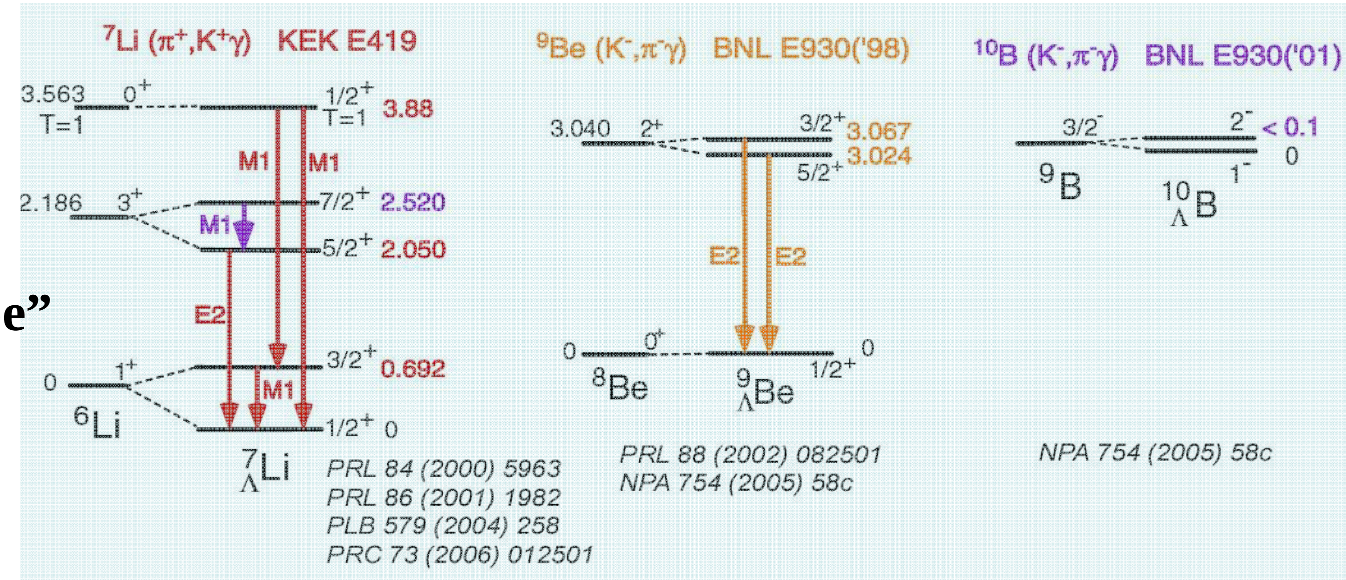


Spin-flip
B(M1) transition

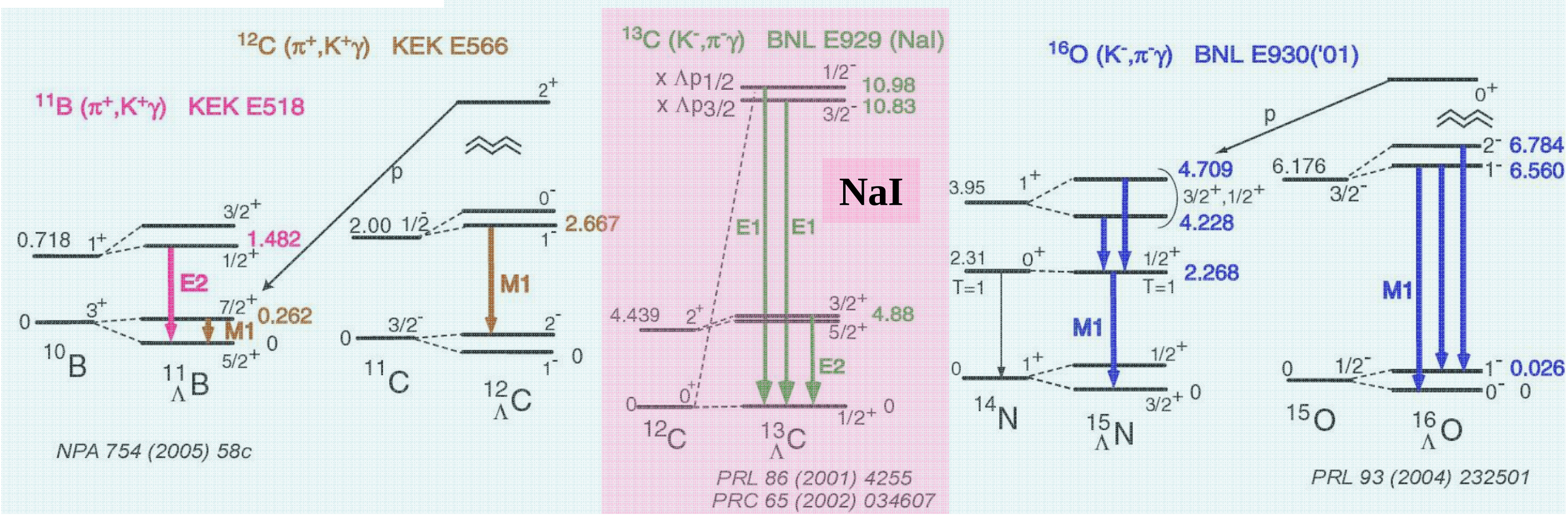
→ Measure τ by <u>Doppler shift attenuation method</u>
Established for "hypernuclear shrinkage" in $^{7}_{\Lambda}$Li from B(E2)
PRL 86 ('01)1982

Results of Hyperball experiment

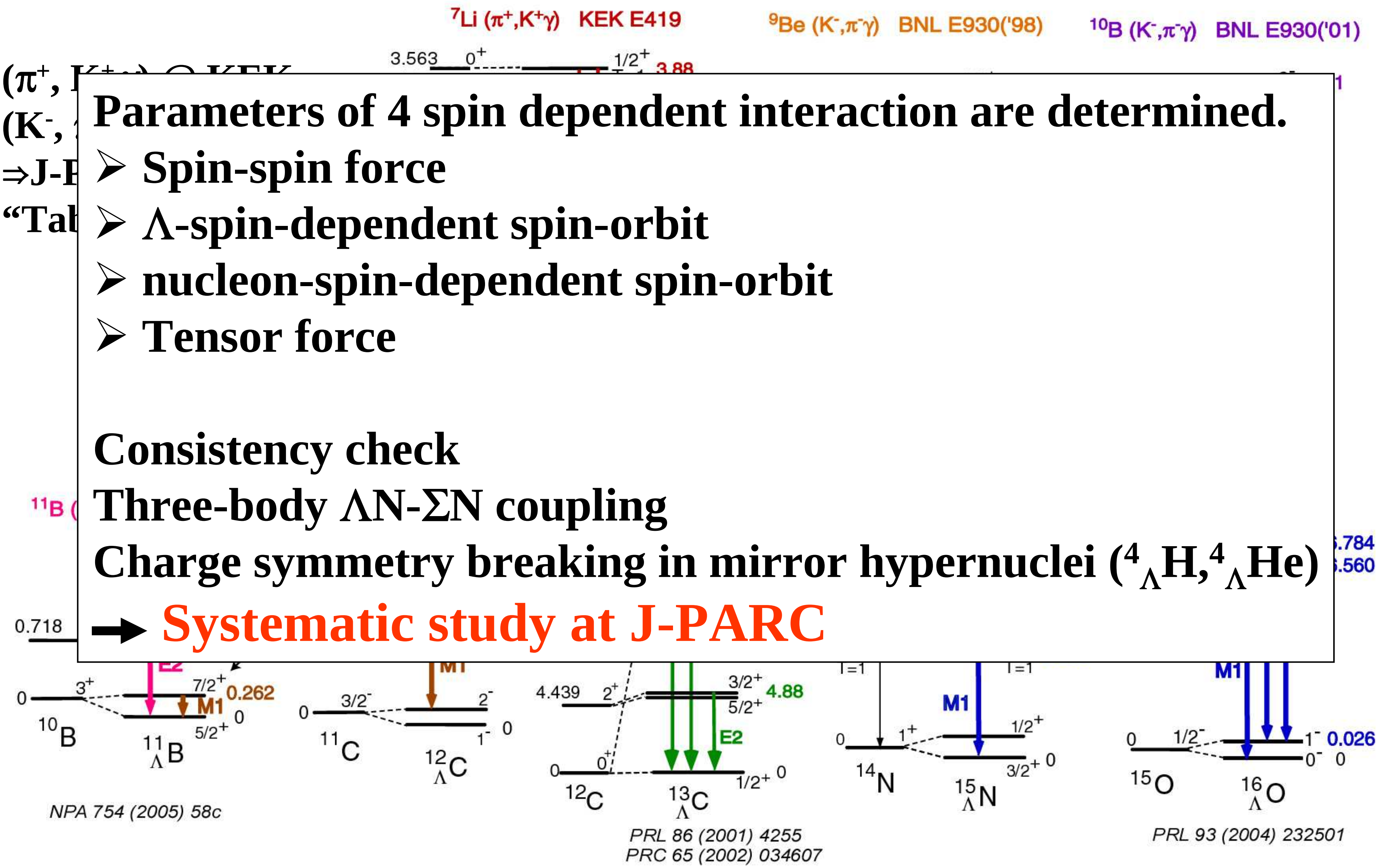
(π^+, $K^+\gamma$) @ KEK,
(K^-, $\pi^-\gamma$) @ BNL
➡ J-PARC
"Table of hyper isotope"



Hyperball



Results of Hyperball experiment



$(\pi^+$, I…

$(K^-$, …

⇒J-I…

“Tal…

Parameters of 4 spin dependent interaction are determined.

- **Spin-spin force**
- **Λ-spin-dependent spin-orbit**
- **nucleon-spin-dependent spin-orbit**
- **Tensor force**

Consistency check

Three-body ΛN-ΣN coupling

Charge symmetry breaking in mirror hypernuclei ($^{4}_{\Lambda}$H,$^{4}_{\Lambda}$He)

→ **Systematic study at J-PARC**

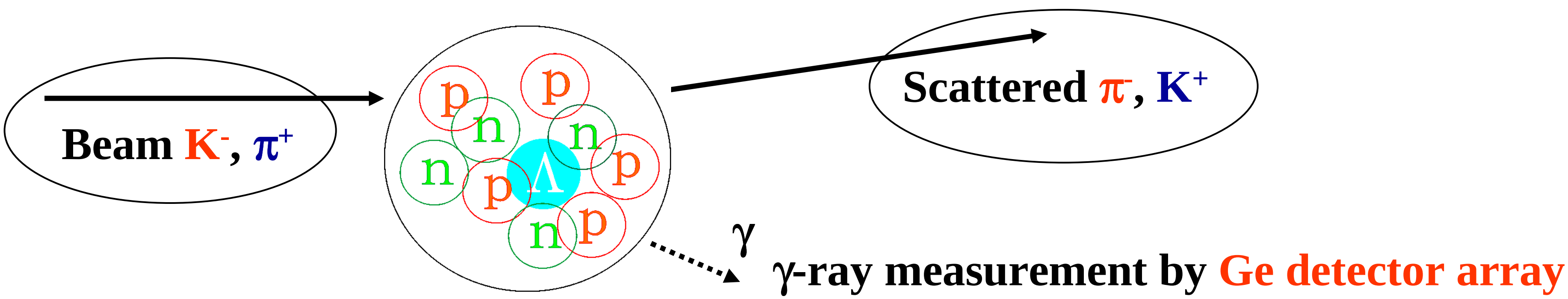
Experimental method and detectors

- **Experimental method**
- **Magnetic spectrometer**
- **Hyperball and Hyperball2**

Hypernuclear γ-ray spectroscopy experiment

Magnetic spectrometer + Hyperball
➡ Huge background
*** To select the bound region of hypernuclei by magnetic spectrometer is essential.**

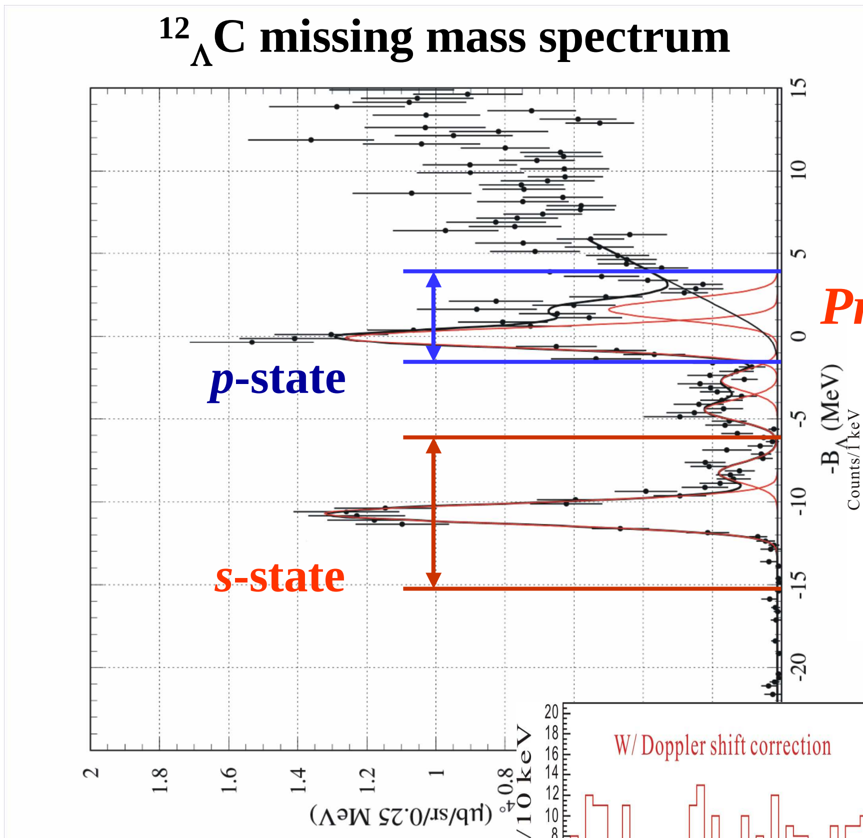
Missing mass analysis : magnetic spectrometers
(identification of hypernuclear bound states)

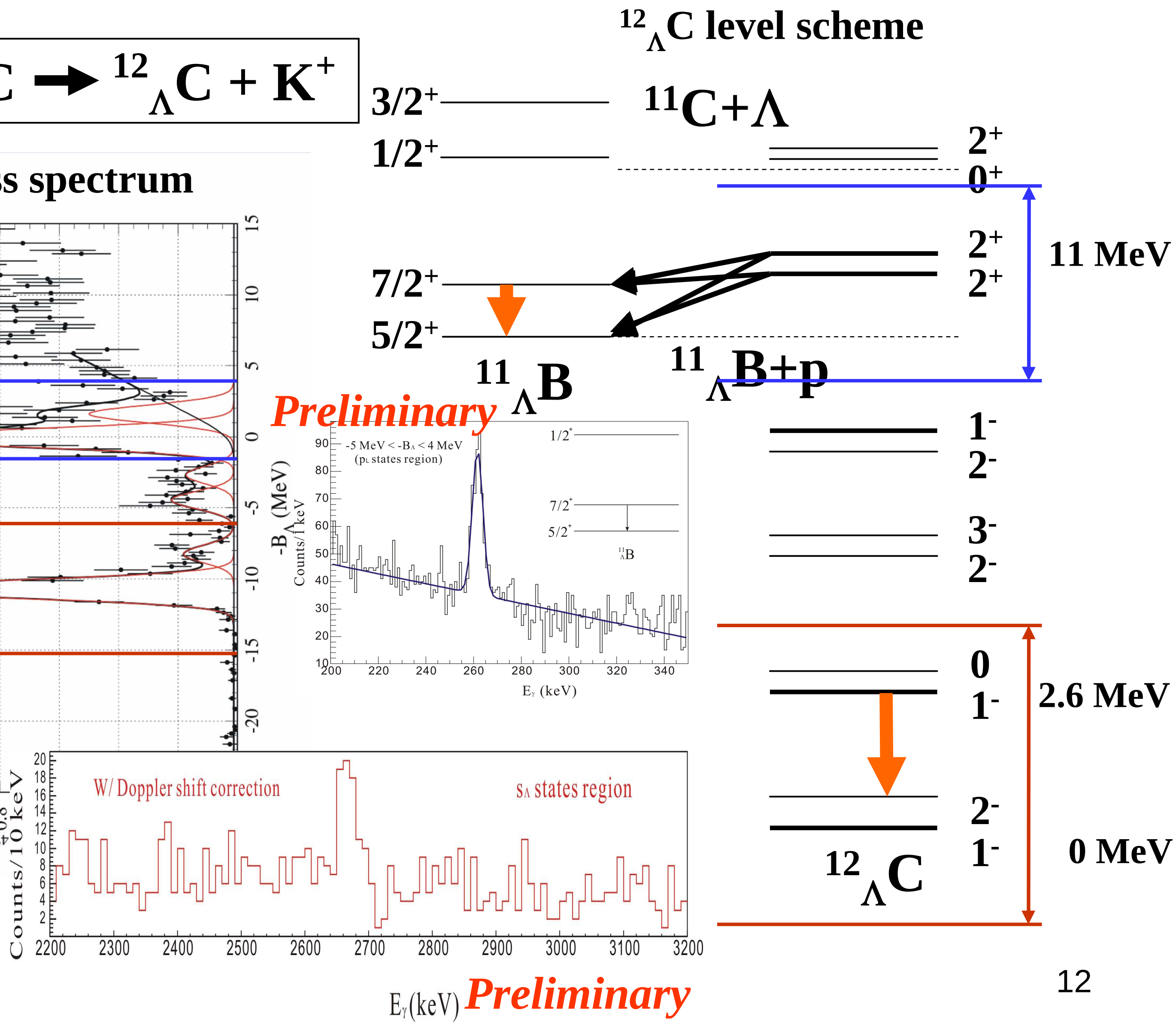


➡ **γ rays from hypernuclei : Reaction-γ coincidence**

Example of reaction-γ coincidence

Reaction : $\pi^+ + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + K^+$



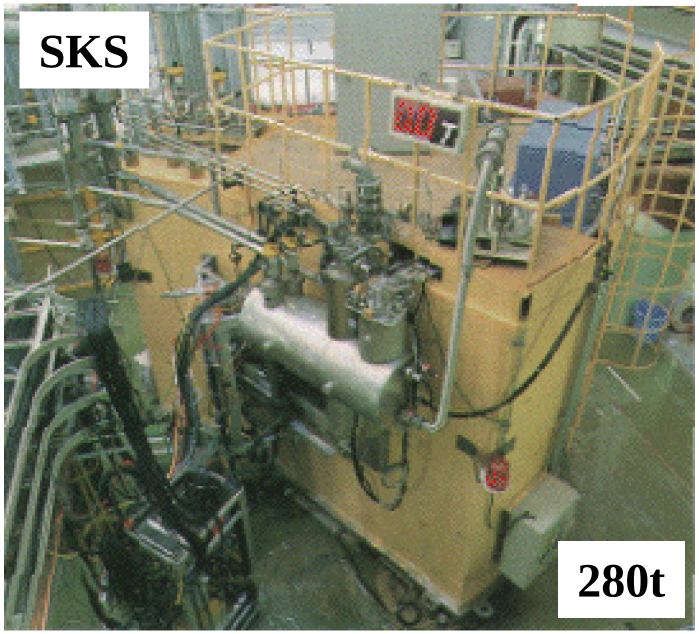


H. Hotchi et al Phys.Rev.C64(2001) 044302

Magnetic spectrometer

Requirements for spectrometer

- Large acceptance ~100 msr, θ=0-20 degree
  → Efficient tagging of hypernuclei and angular selectivity
- Good momentum resolution 2-4 MeV/c (FWHM)
  → Identification of bound states of hypernuclei (mass resolution ~5 MeV (FWHM))
- Particle identification

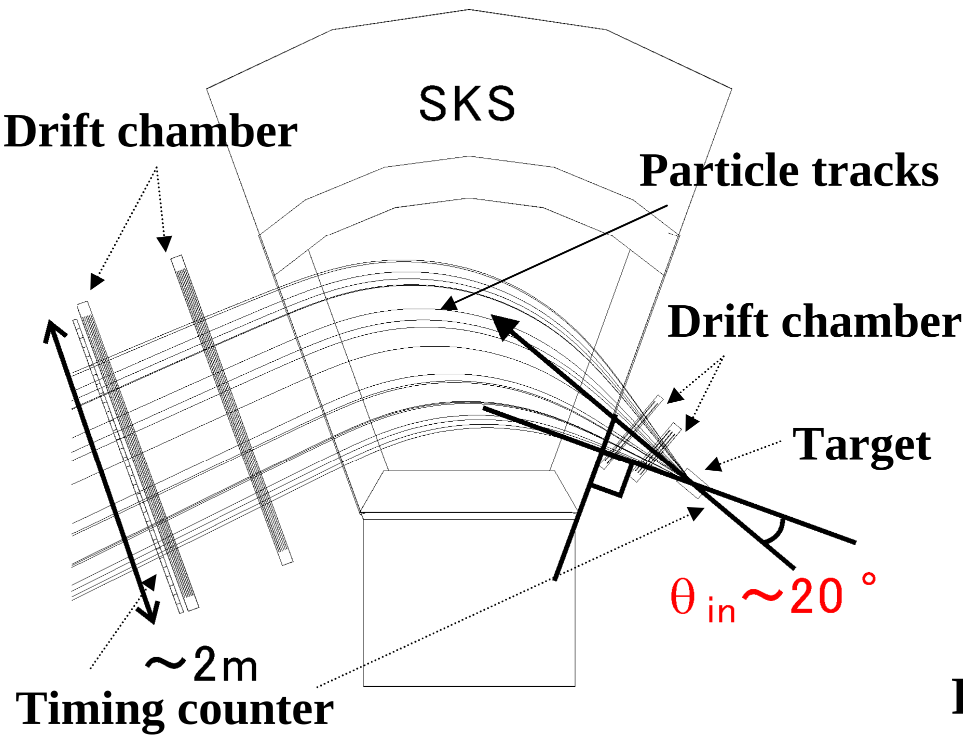


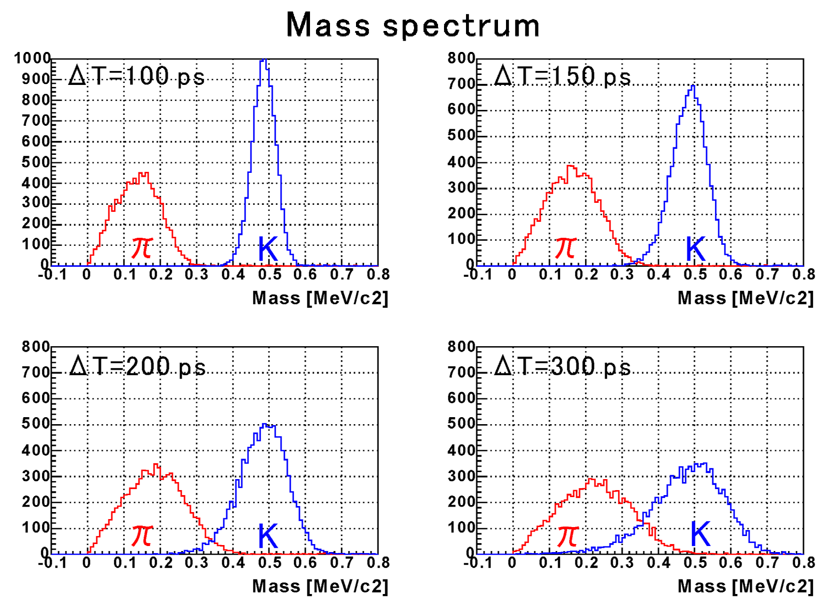
SKS@KEK

Momentum resolution	0.1%FWHM (0.72 MeV/c) @ 720 MeV/c, 2.2T
Acceptance	100 msr @ 0.72GeV/c
Maximum central momentum	1.0 GeV/c @ 2.7T

Design of magnetic spectrometer

SKS system designed by *Geant4* simulation for J-PARC





Scattered particles are measured by drift chambers.

➡Optimize the configuration to maximize the acceptance

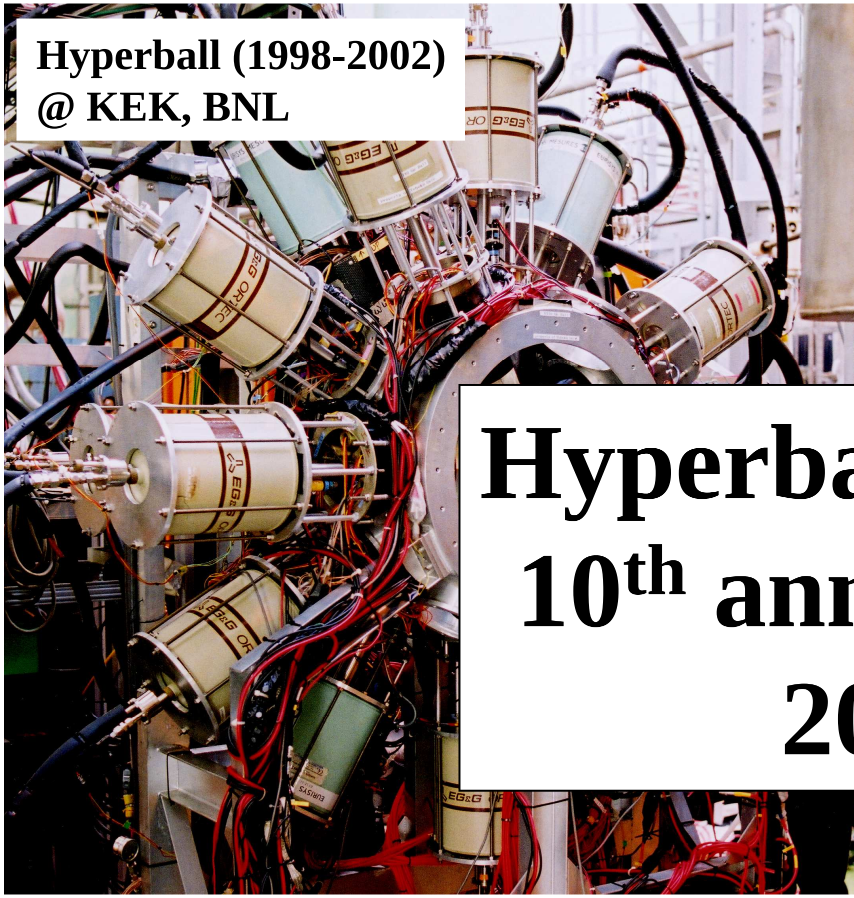
PID from Time-Of-Flight

➡To estimate requested time resolution

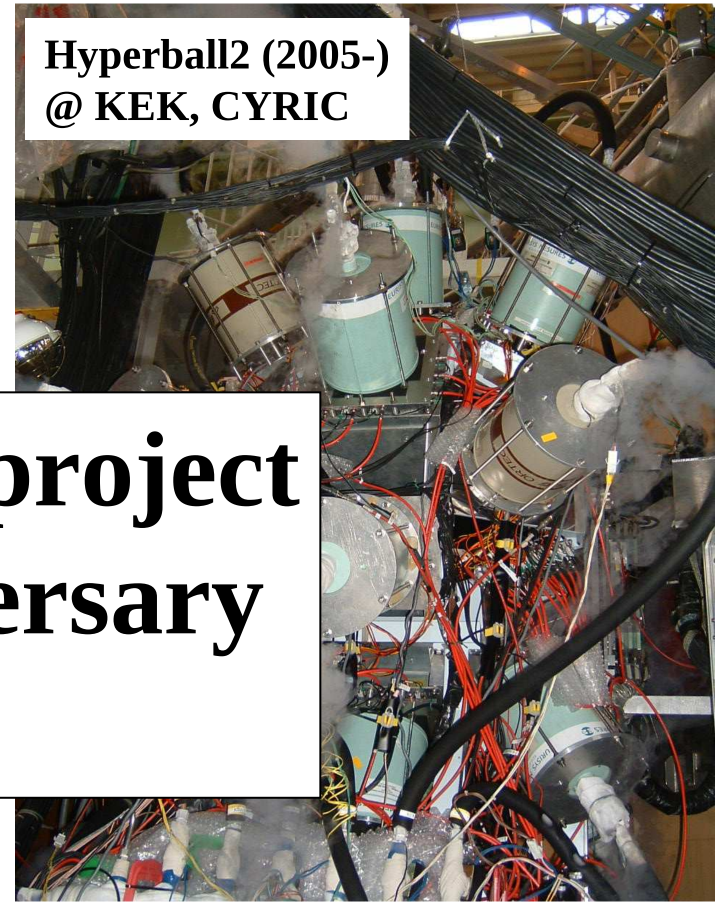
Not only the design of Ge detector array but also magnetic spectrometer

Hyperball-J

Hyperball and Hyperball2



Hyperball (1998-2002)
@ KEK, BNL



Hyperball2 (2005-)
@ KEK, CYRIC

Hyperball project
10th anniversary
2008

14 single type Ge detectors (60%)
+ BGO counter
ε_γ~2.5%

14 single type Ge detectors (60%)
6 clover type Ge detector (120%)
+ BGO counter
ε_γ~4%

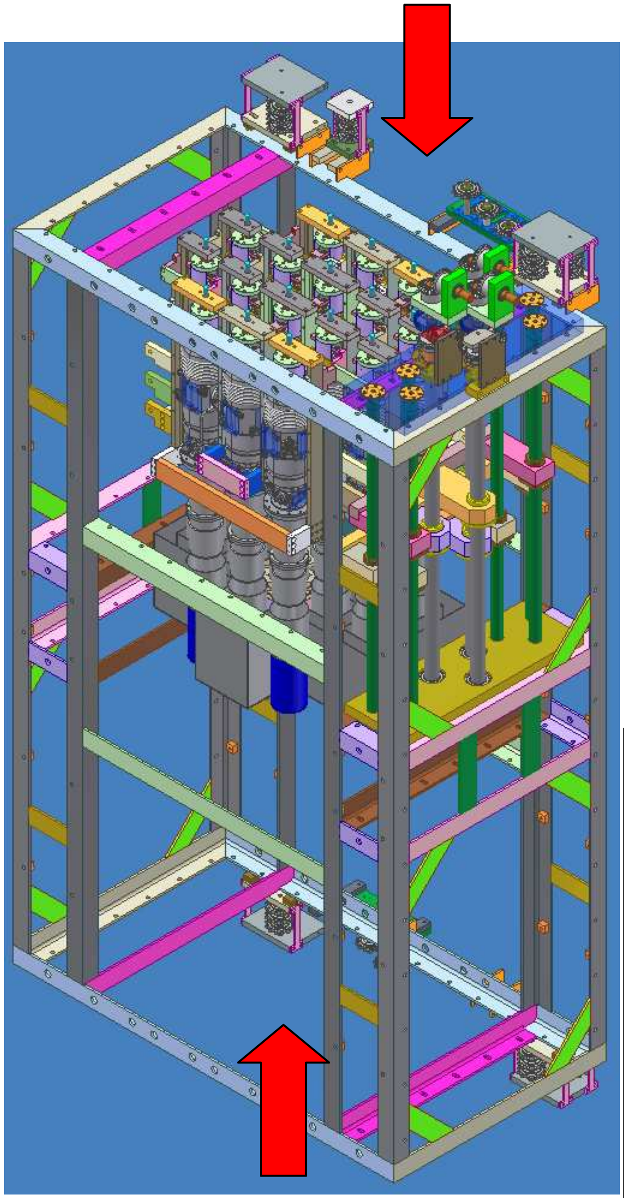
Technicalities of hypernuclear γ-ray spectroscopy

- High energy mesonic beams (π and K)
  - A large energy deposit (~50 MeV) by penetrating π
  - High energy deposit and counting rate on Ge det.
    - 0.5 TeV/s &50 kHz
  - Transistor reset preamp with low gain 150 MeV/reset (30 MeV/reset for Gammaspher)
  - Use of Ultra high rate amp. (ORTEC 973U) with GI
  - Sever neutron damage
  - No beam duct

- Typical experiments
  - ~1 month beam time
  - A tick target ~20g/cm^2

Hyperball-J Ge array at J-PARC

Planar arrangement



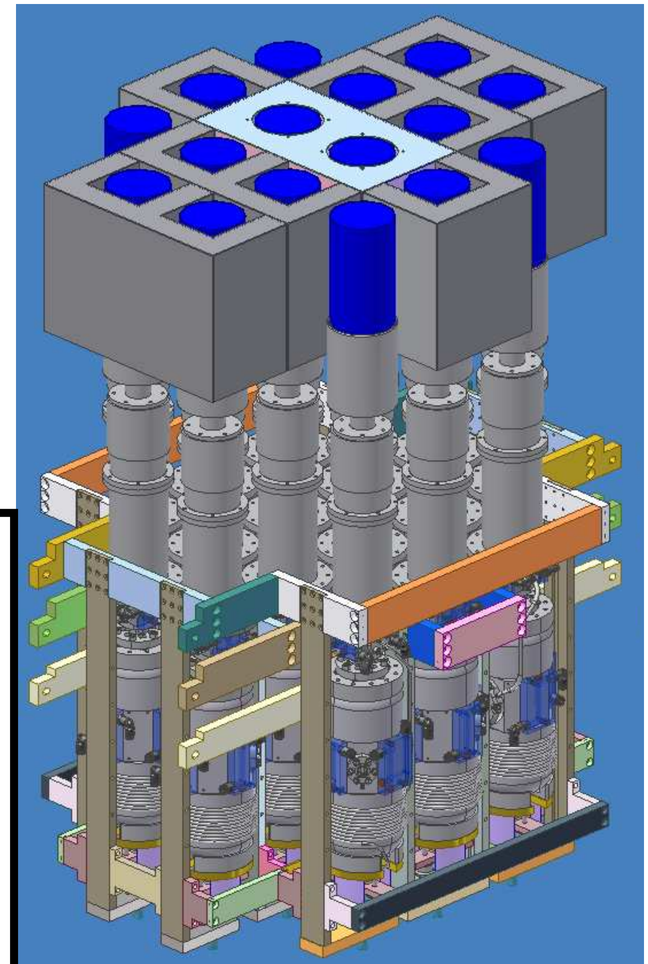
Designed by N. Chiga

Ge detector ×32
 -70% relative eff.
 -N-type
 -Transistor reset type
 (150 MeV/reset)
Total photo peak eff.
~6% for 1 MeV γ ray

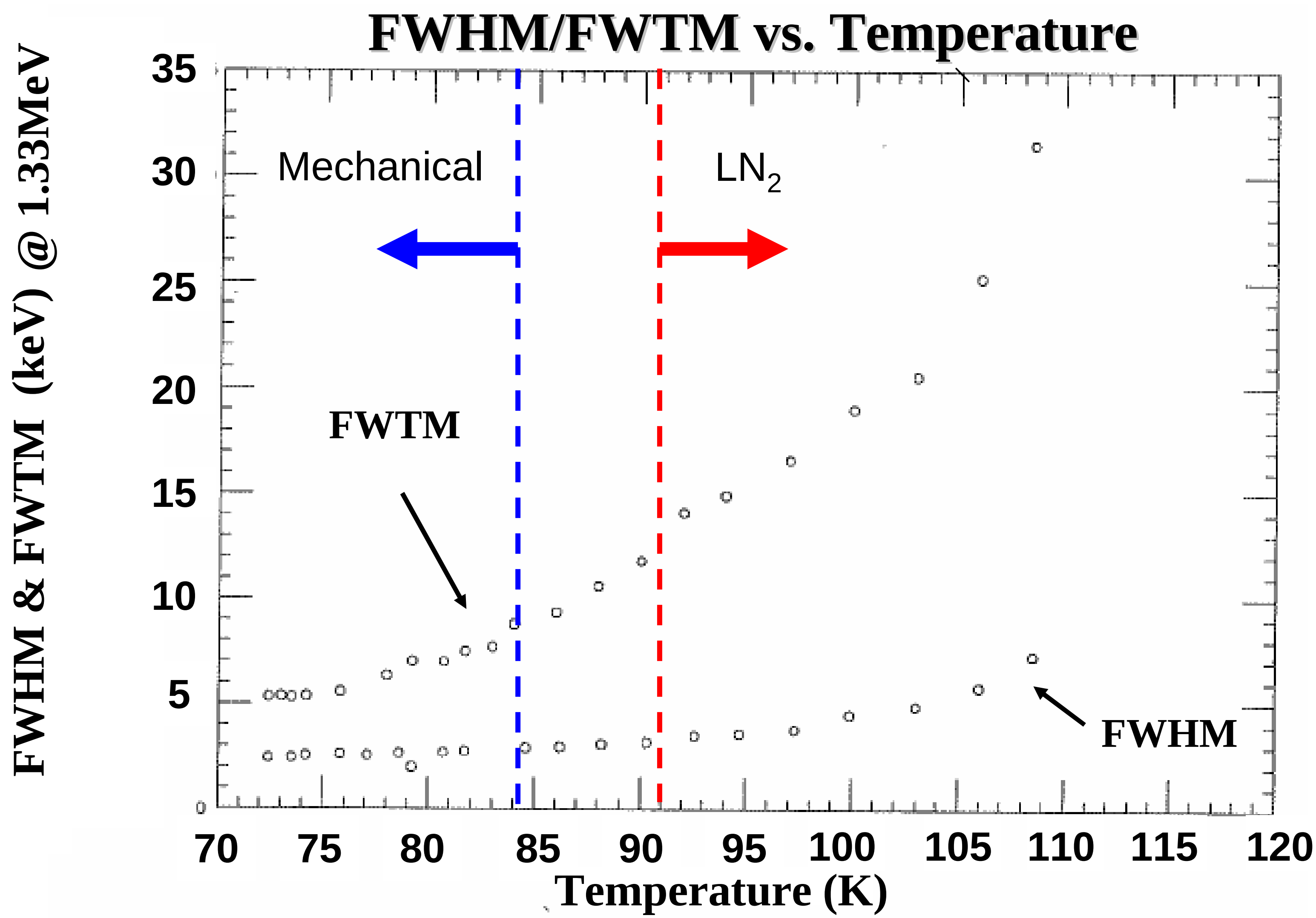
R&D

- Mechanical cooling
  - Radiation damage
- PWO suppression
  - Fast suppressor
- Waveform analysis
  - Pileup and baseline restoration

Half the array shown

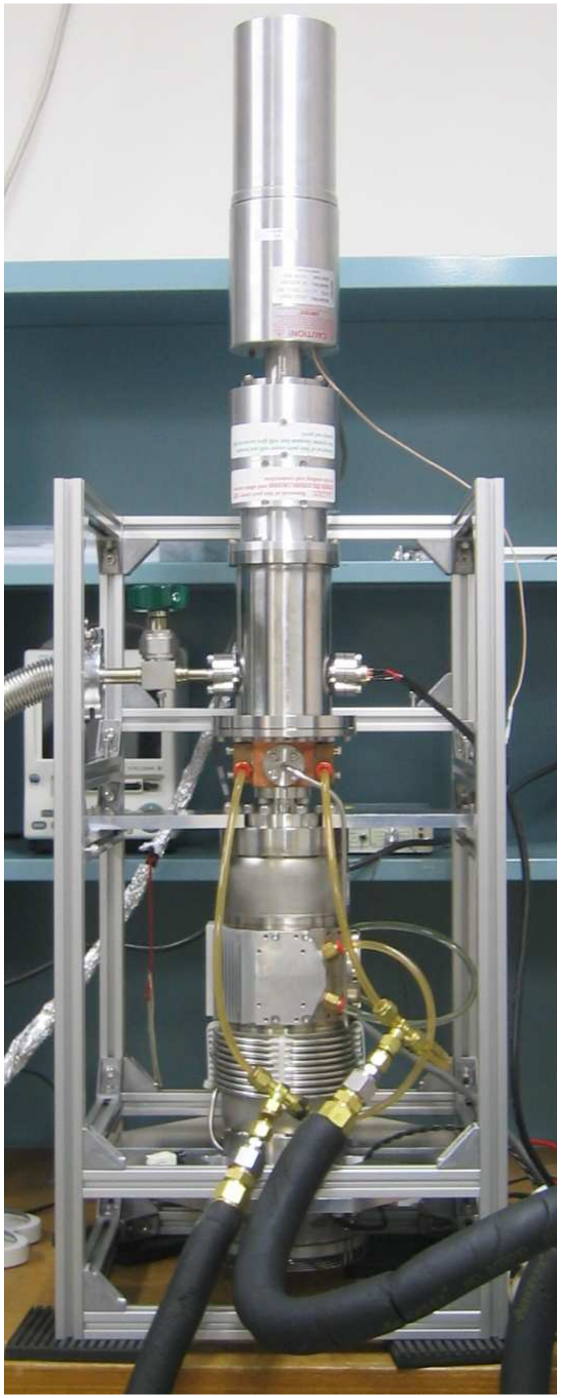


Temperature dependence of neutron damage on Ge det. resolution



183MeV neutron of 3.2×10^8 n/cm^2 irradiated on n-type coaxial detector

E. Hull and R. H. Pehl et al., IUCF Ann. Rep. 143, (1993)



Mechanical cooling of Ge detectors

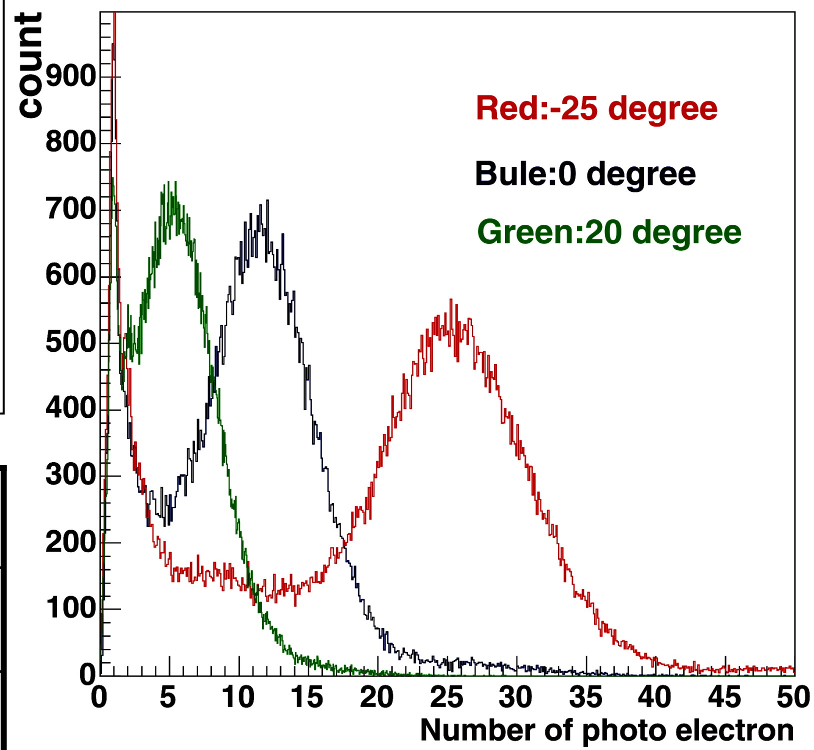
- Pulse Tube refrigerator
  - Fuji electric systems
- Transplantable Ge det. design
- Pulse tube mounted (Dec.,2007)
  - Input power: 160 W
  - Water cooling + Fan
  - C/H: 57 K
  - Ge crystal: 71 K (Bias off 69 K)
- Resolution (needs improvement)
  - LN_2 2.1 keV (at ORTEC & SEIKO)
  - LN_2 3.0 keV(2.3 keV) at KEK
  - Pulse Tube: 4.5 keV(4.0 keV)

PWO back ground suppressors

•BGO crystal (τ~300 ns) too slow to be used at J-PARC
➞PWO crystal (τ~6 ns)
•Small light yield of PWO crystal➞Doping and cooling of the crystal

Crystal	BGO	PWO
Decay constant [ns]	300	~6
Radiation length (cm)	1.12	0.89
Light yield [NaI=100]	15	~1

Number of photo electron for 661 keV γ ray



Summary

- Hypernuclear γ-ray spectroscopy
  - Extending the nuclear chart into strange sector
  - ΛN interaction as the first step to investigate B-B interaction
  - Nuclear medium effect on Λ
- SKS & Hyperball-J at J-PARC
  - Reaction-γ spectroscopy
  - Hyperball-J Ge array
    - Planar arrangement
    - Pulse Tube cooling
    - PWO background suppressor

Thank you

Backup

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

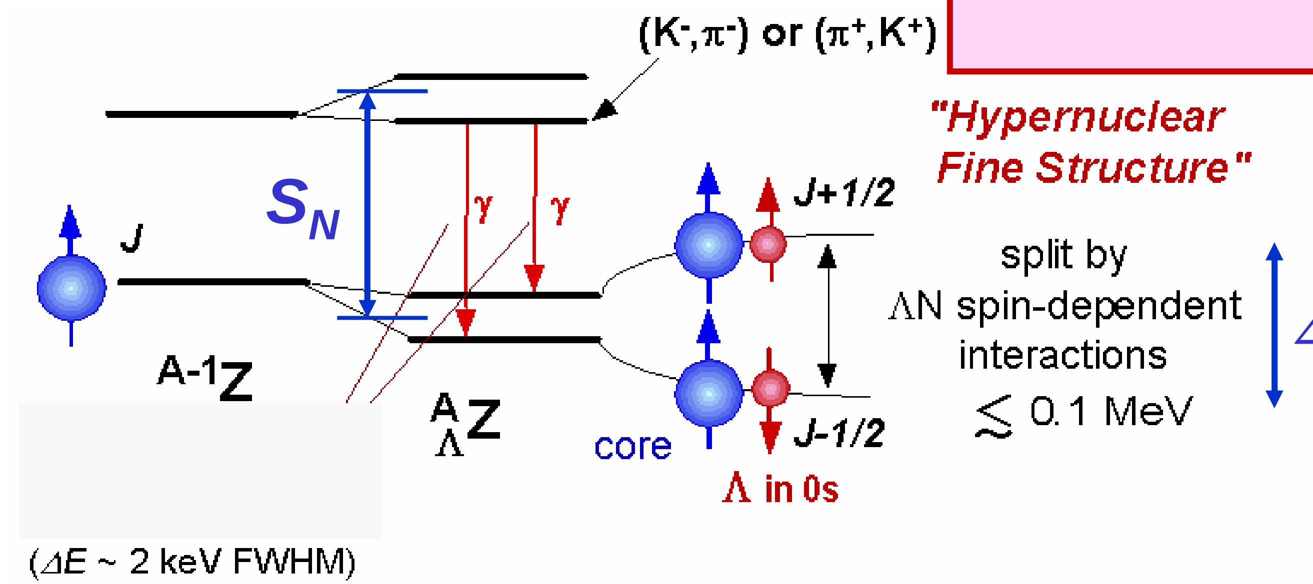
p-shell: 5 radial integrals for $p_\Lambda s_\Lambda$ w.f.

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

Well know from U_Λ = - 30 MeV

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

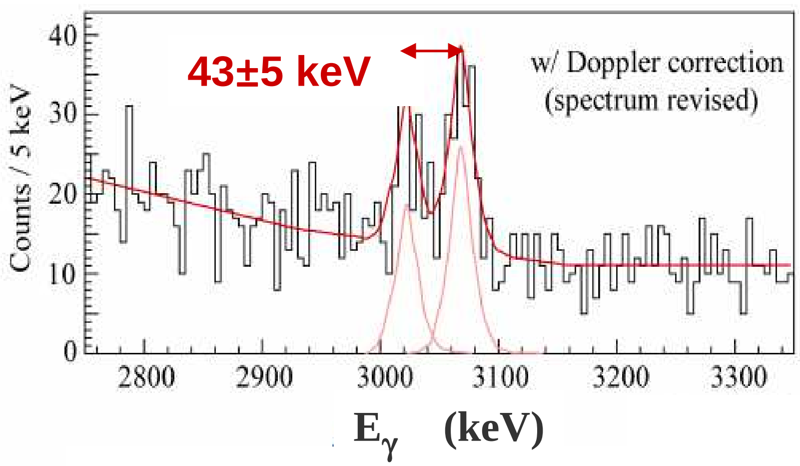
Level spacing: linear combination of Δ, S_Λ, S_N, T

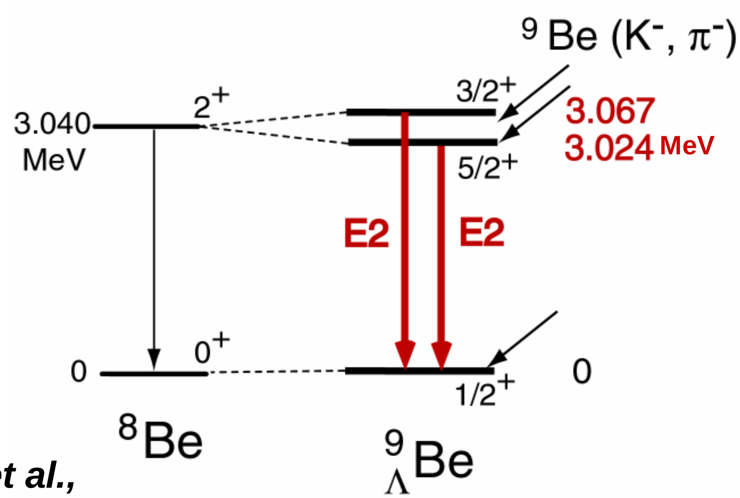


Observation of Hypernuclear Fine Structure

BNL-AGS E930

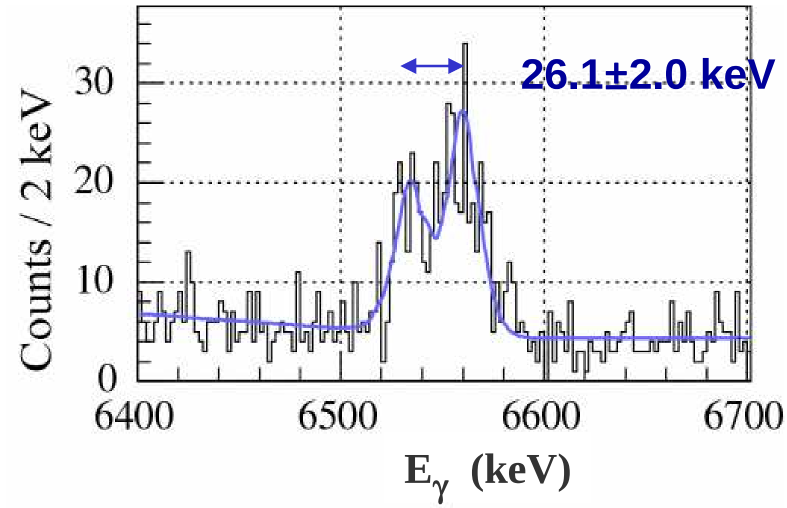
$^{9}Be\ (K^{-}, \pi^{-}\ \gamma)\ ^{9}_{\Lambda}Be$

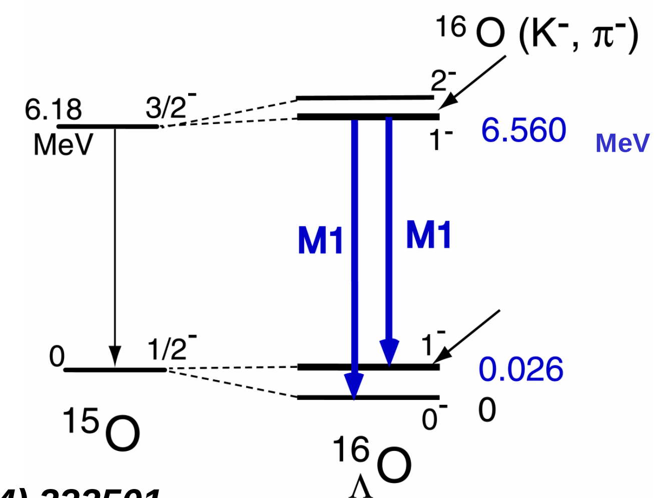




Akikawa et al., PRL 88 (2002) 082501

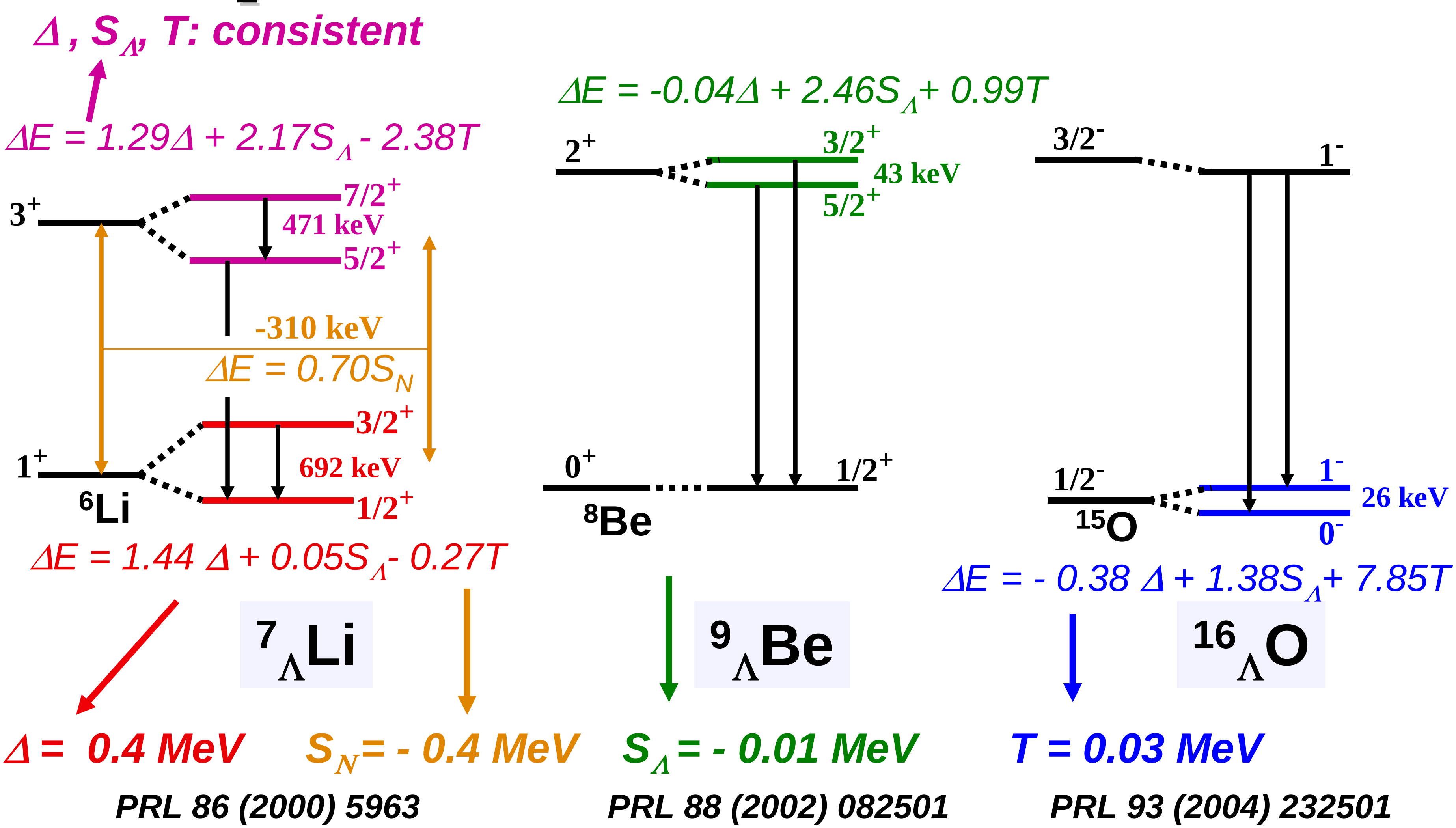
$^{16}O\ (K^{-}, \pi^{-}\ \gamma)\ ^{16}_{\Lambda}O$





Ukai et al., PRL 93 (2004) 232501

Determination of the spin-dependent force parameters



All the spin-dependent force parameters determined.

Feedback to BB interaction models

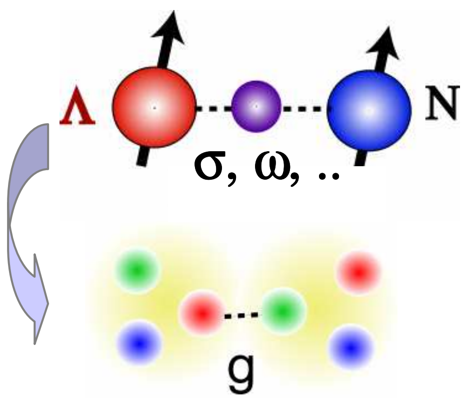
Nijmegen meson-exchange models

	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

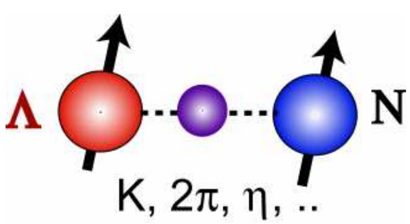
G-matrix calc. by Yamamoto (ND, NF, NSC89, NSC97f)

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.



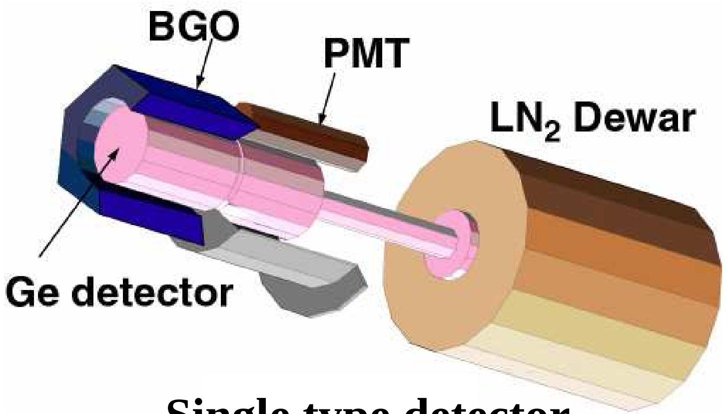
Origin of the ΛN spin-orbit force
=> Quark-gluon exchange
rather than heavy meson exchange
Should be the same for the large NN spin-orbit force



Origin of ΛN tensor force
=> Meson exchange. Same as NN tensor force

Ge detector and BGO counter

Beam intensity : ~10^6 Hz
➢ Hadron beam : Beam halo (~15 cm), many scattering particles from target (target size ~10 g/cm^2)
⇒High counting rate and many background



Single type detector

Ge detector
* Counting rate : 50-100 kHz
➢ Transistor reset type preamp
➢ Gated-integrator shaping amp

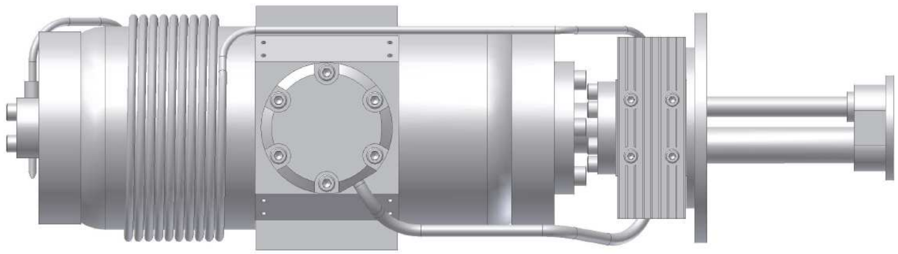
Dead time : ~50 %
Radiation damage

BGO counter
* Background suppression
➢ Compton scattering
➢ Charged particles
➢ π^0 decay γ ray

Overkill : ~10 %

3 essential requirements for mechanical cooling of Ge det. for Hyperball-J

- **Cooling power**
  - Ge crystal temperature less than 85K when biased
- **Low mechanical vibration**
  - Minimization of microphonics noise
- **Compact size**
  - Realization of the planar arrangement of Ge detectors



- Pulse Tube Refrigerator
  - Fuji Electric systems Co. Ltd.
- 5W at 77K
  - Input power: 160W
  - Ambient temp. 25℃
- Weight 8.5kg
- 50,000 hours maintenance free operation

Summary

- Study of Λ hypernuclei
  - ΛN interaction
  - Nuclear medium effect
- Spin dependent interaction
  - Small energy spacing ⇒ Ge detector : Hyperball
  - Essential parameters determined by the past experiments
- Hypernuclear γ-ray spectroscopy
  - Particle-γ coincidence
- Ge detector array: Hyperball and Hyperball2
- Magnetic spectrometer: SKS