γ-ray spectroscopy of hypernuclei with Hyperball-J at J-PARC

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Contents

- What are hypernuclei and why interesting?
- Hypernuclear γ-ray spectroscopy
  - Recent results from E566 analysis: $^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C
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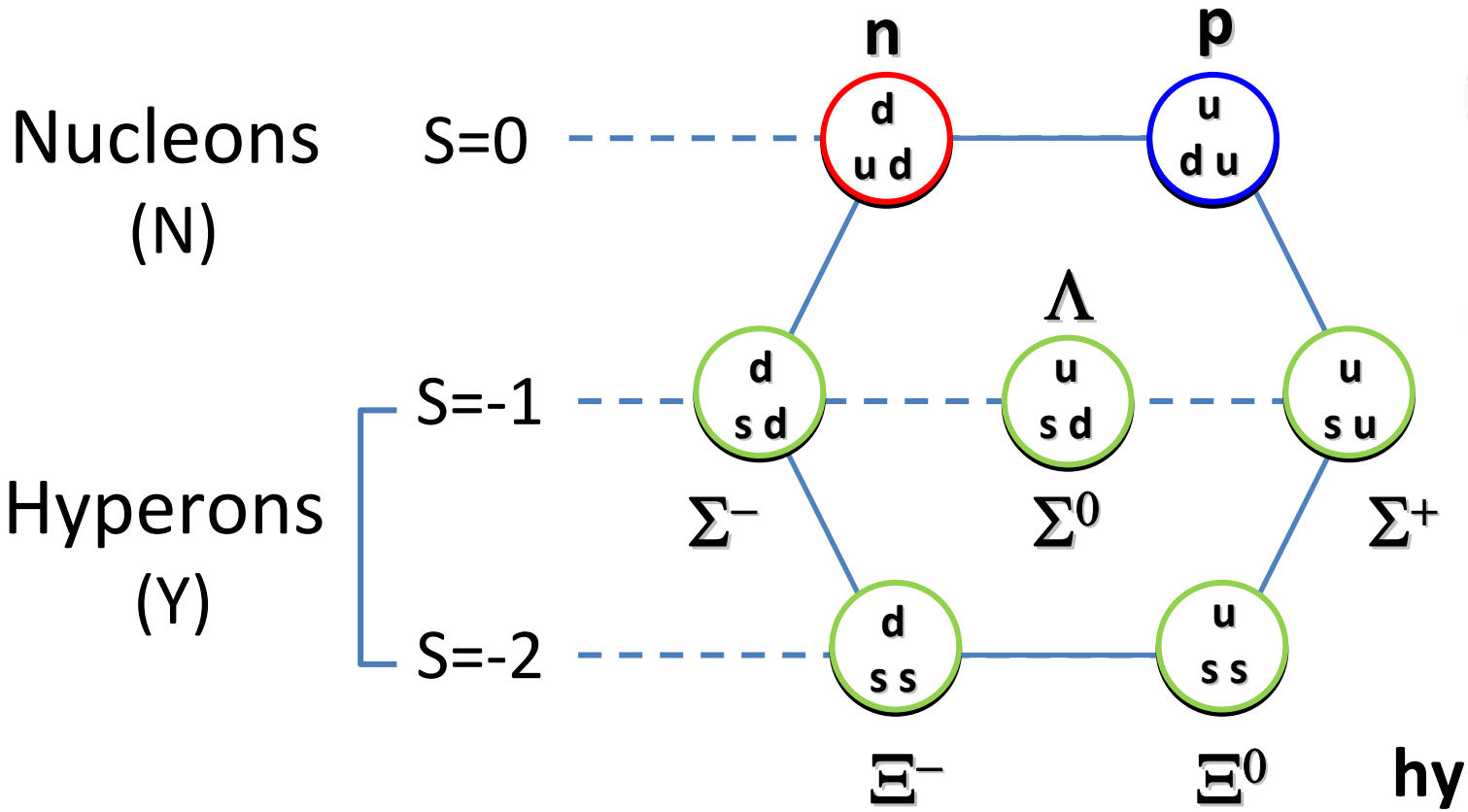
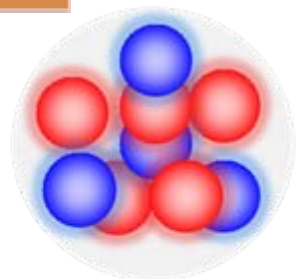
- J-PARC and Hyperball-J
- *sd*-shell hypernuclei
- Summary

Introduction
- What are hypernuclei ?-

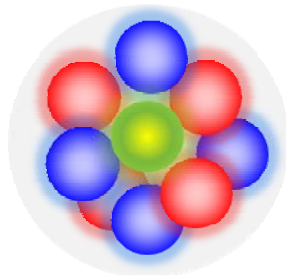
Nuclear physics with strange quarks

+2/3e	*u* (p) ~ 0.003 Gev	*c* (harm) ~ 1.3 GeV	*t* (op) ~ 171 GeV
-1/3e	*d* (own) ~ 0.005 GeV	*s* (trange) ~ 0.01 GeV	*b* (eauty) ~ 4.3 GeV



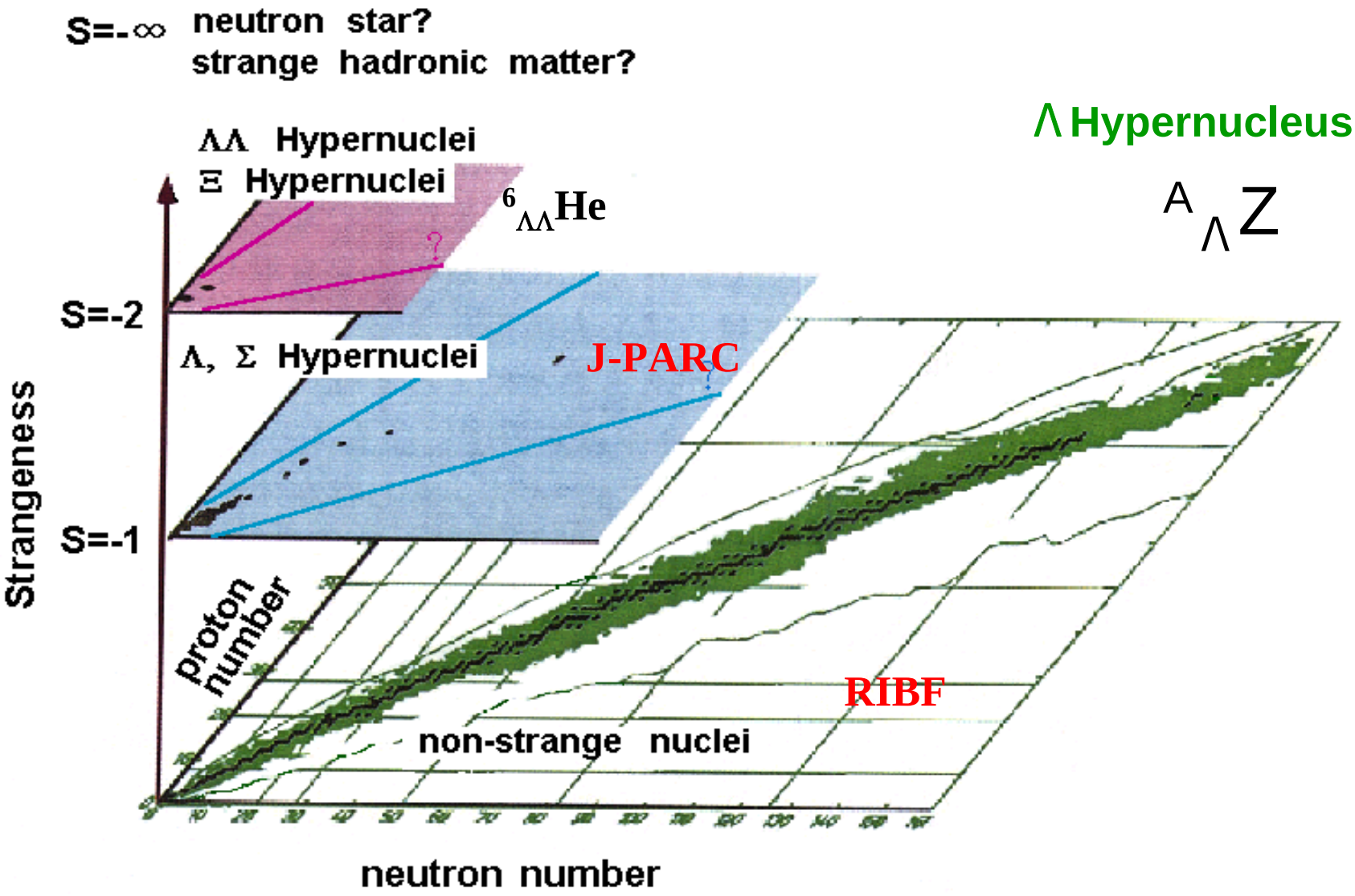


nucleus



hyper nucleus

3D nuclear chart



Λ Hypernucleus : $^{A}_{\Lambda}Z$

Rare opportunities in Japan

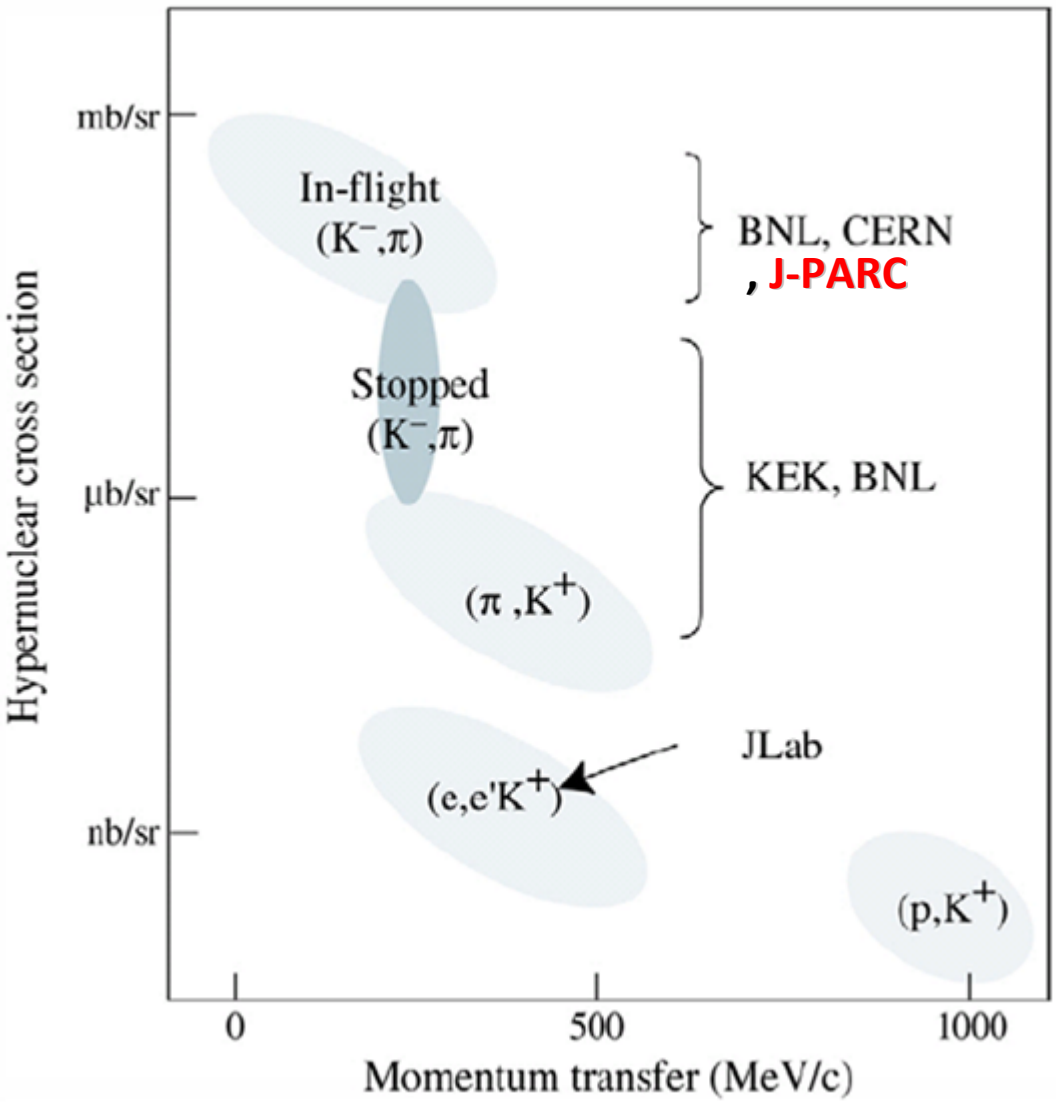
Properties of Λ

- Mass: 1116 MeV (the lightest hyperon)
- uds
  - S=−1
  - Spin & parity: $I=1/2^+$
  - Isospin: $T=0$
- Lifetime:
  - τ_Λ=263ps (free space), 100～200ps (in nucleus)
- Weak decay mode
  - $\Lambda \rightarrow p+\pi^-$ (Q=38MeV)
  - $\Lambda \rightarrow n+\pi^0$ (Q=41MeV)

  Mesonic
  - $\Lambda n \rightarrow n+n$ (Q=176MeV)
  - $\Lambda p \rightarrow p+n$ (Q=176MeV)

  Non-mesonic **(only in nucleus)**

Production of Λ hypernucleus



$K^- + n \rightarrow \Lambda + \pi^-$

- Strangeness exchange
- small momentum transfer
- substitutional
- secondary beam

$\pi^+ + n \rightarrow \Lambda + K^+$

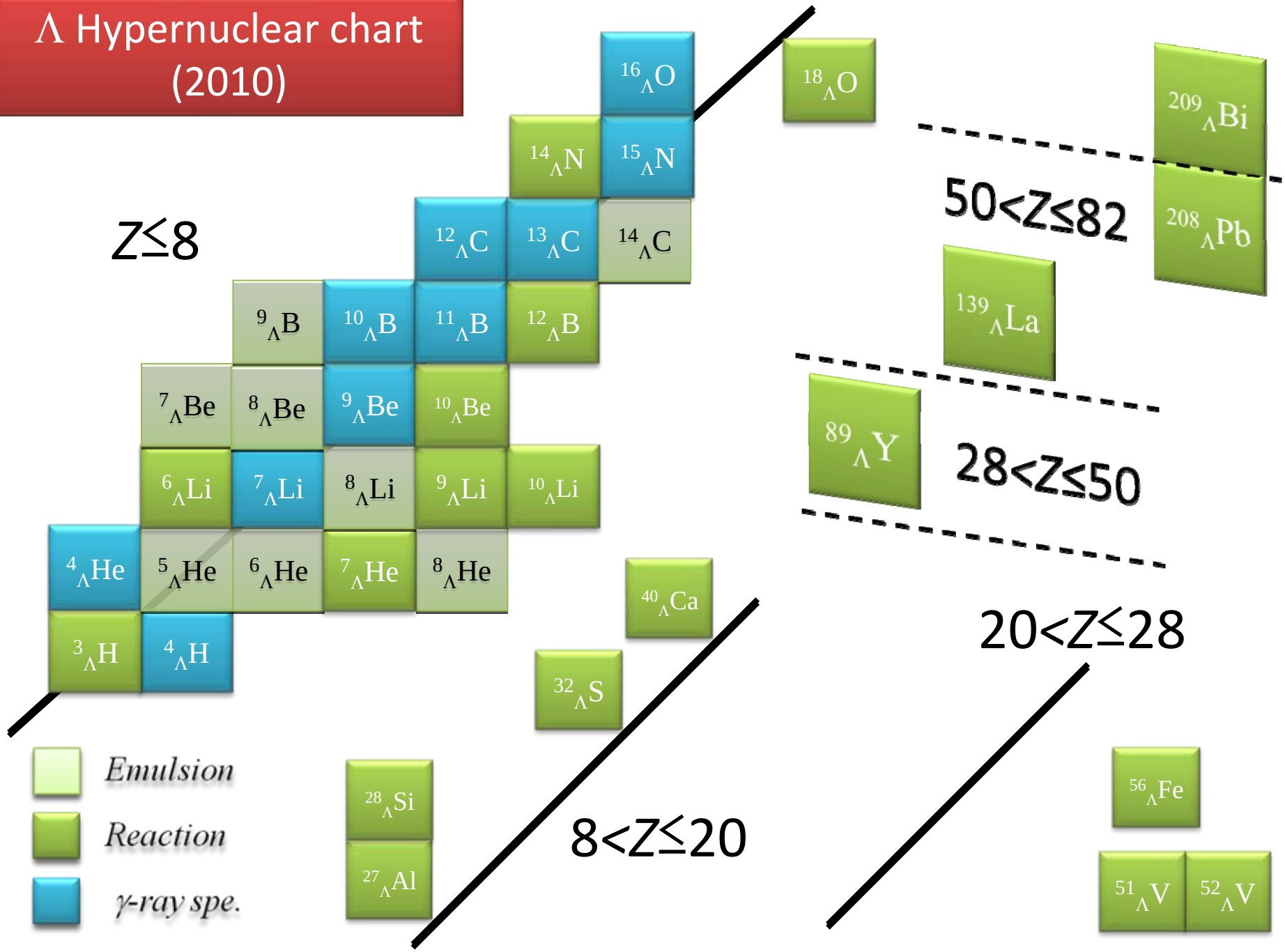
- Associated strangeness production
- large momentum transfer
- stretched, high spin
- secondary beam

$e + p \rightarrow \Lambda + e' + K^+$

- Electro production
- spin-flip
- primary beam

O. Hashimoto, H. Tamura / Progress in Particle and Nuclear Physics 57 (2006) 564–653

Λ Hypernuclear chart (2010)



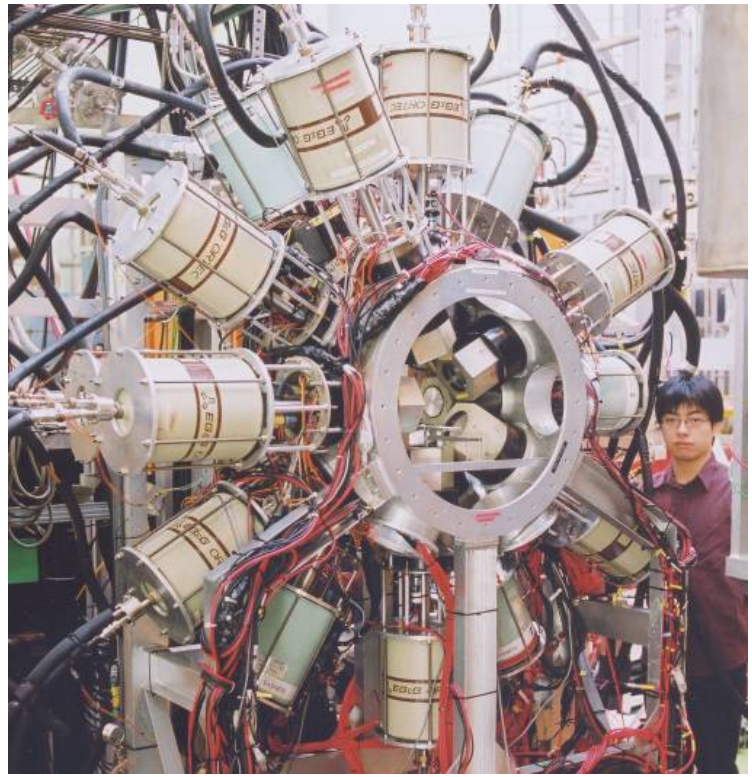
Based on *O. Hashimoto, H. Tamura / Progress in Particle and Nuclear Physics 57 (2006) 564–653*

Hyperball

~ the world first Ge det. array

for hypernuclear γ-ray spectroscopy~

- **Technique pioneered by H. Tamura in 1998**
- **14 co-axial N-type Ge detectors**
- **BGO background suppressors**
- **2.5% total photo peak efficiency at 1 MeV**



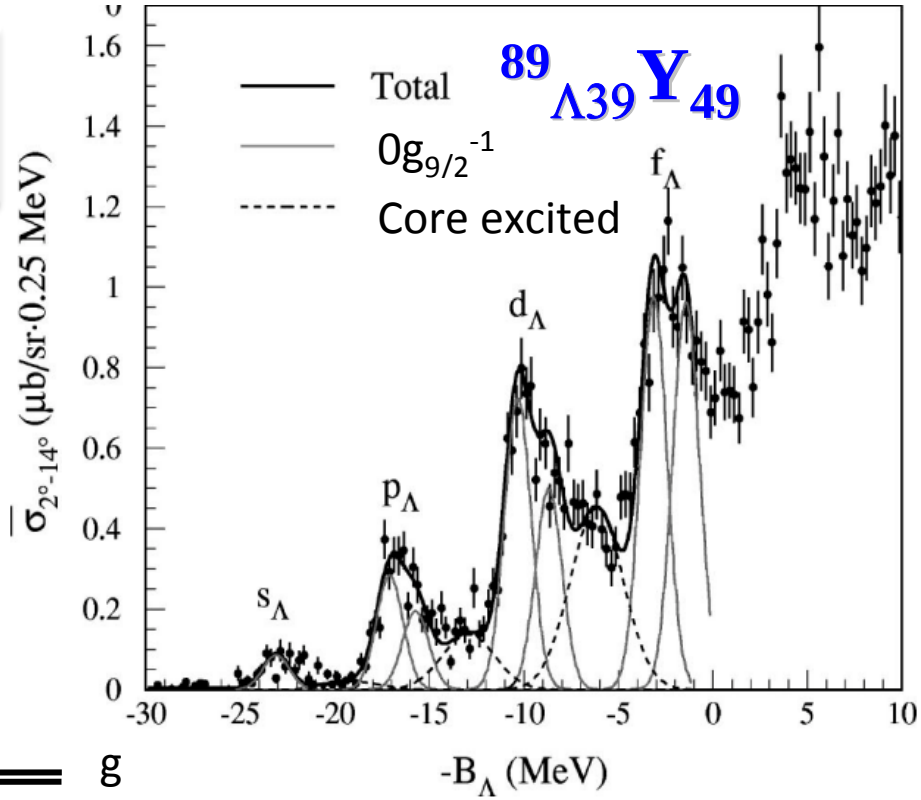
Hyperball 1998~2004
BNL and KEK

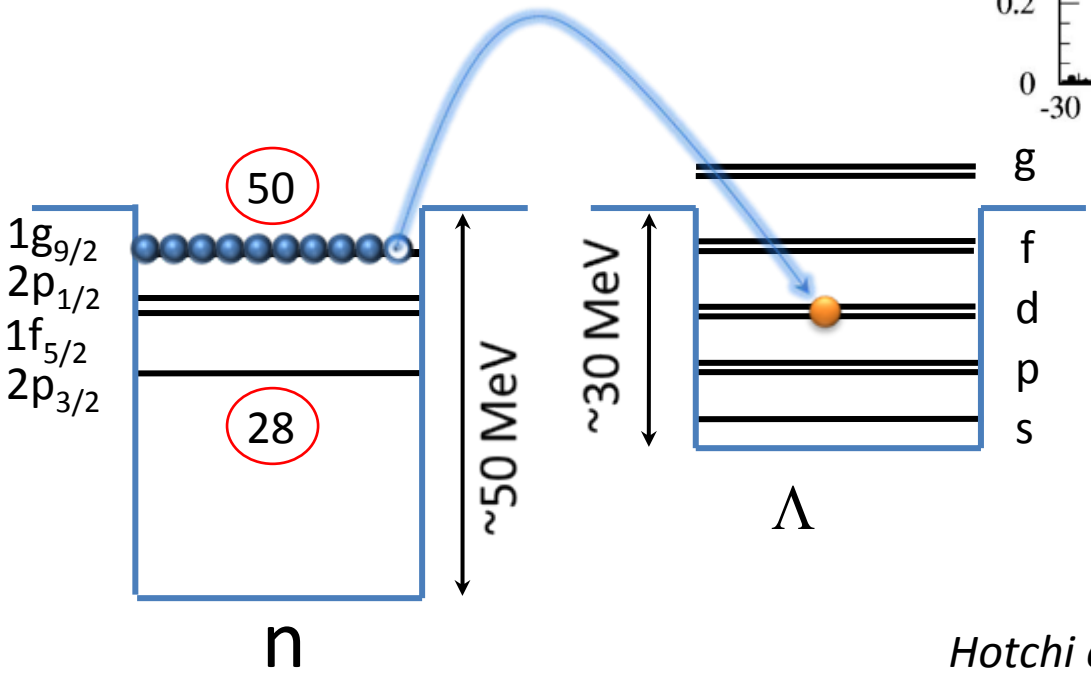
Introduction
- the physics -

Λ as a nuclear probe: shell structure

Strangeness: a new degree of freedom in nuclear matter

No Pauli blocking from nucleons
- Can occupy any orbits
- Unique probe of looking deep into the nuclear interior

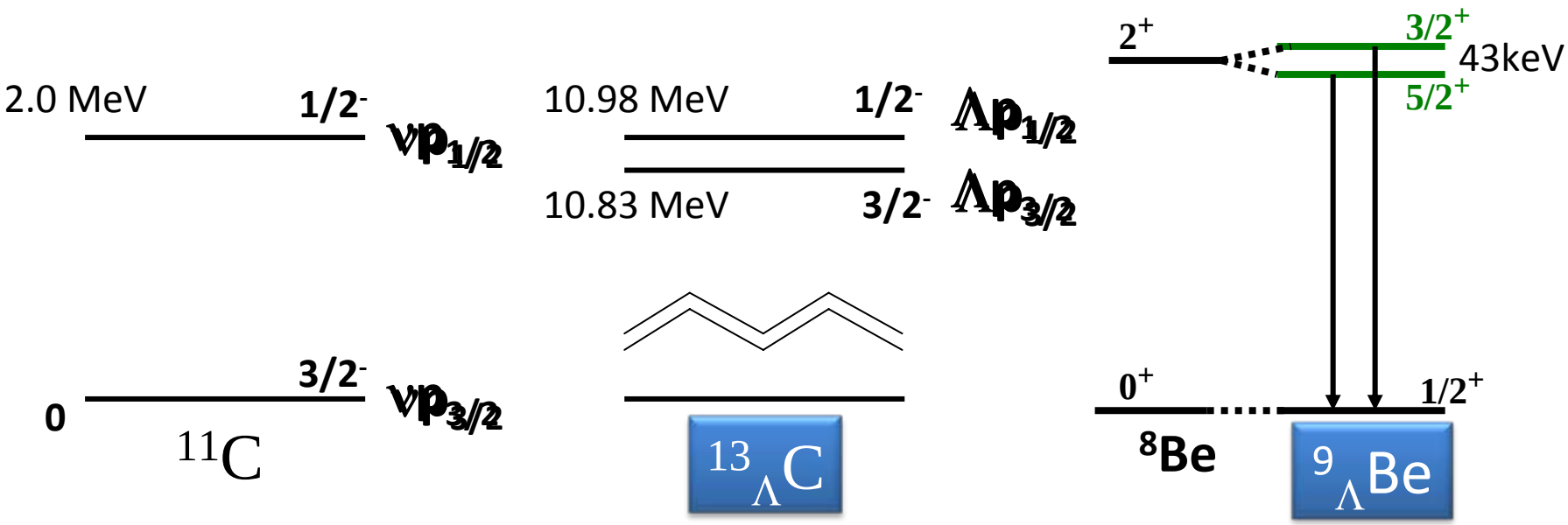


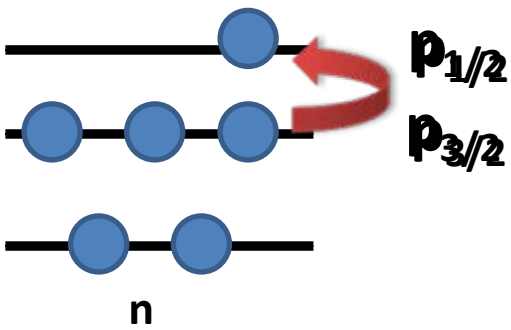


$^{89}Y(\pi^+,K^+)^{89}_{\Lambda}Y$
KEK E369
Counter experiment:
SKS magnet
FWHM= 1.6 MeV

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

Magic number : Spin-orbit force





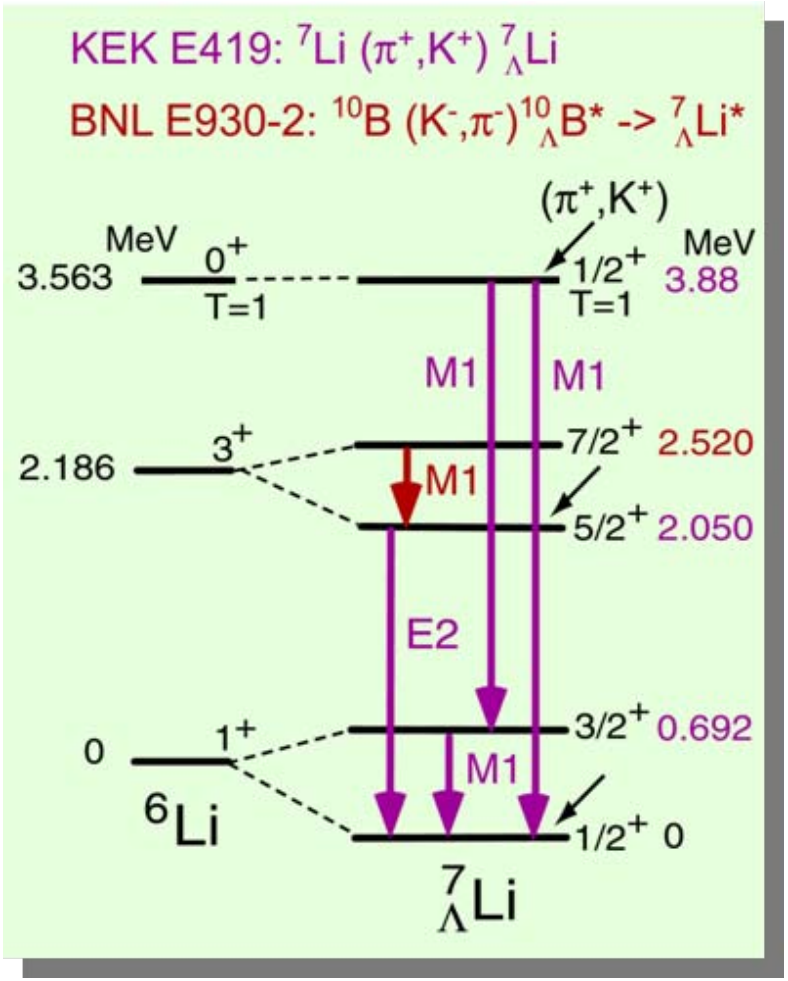
$^{13}C(K^-,\pi^-)^{13}_{\Lambda}C$
BNL E929
γ-ray spectroscopy
NaI(Tl) array

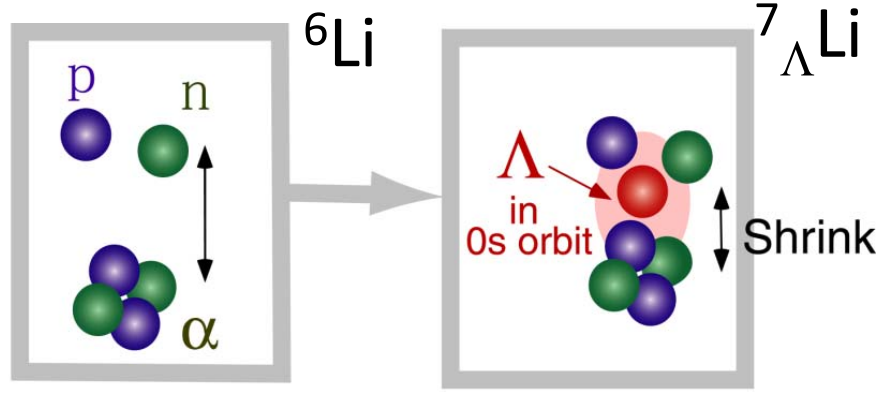
*PRL **86** 4255(2001)*
*PRC **65** 034607(2002)*

$^{9}Be(K^-,\pi^-)^{9}_{\Lambda}Be$
BNL E930 ('98)
γ-ray spectroscopy
Ge array (Hyperball)

H. Akikawa et al.,
*PRL **88** 082501(2002)*

Nuclear matter incompressibility





B(E2) [e^2 fm^4]

$10.9 \pm 0.9 \rightarrow 3.6 \pm 0.5 \pm^{0.5}_{0.4}$

⇒ 19±4% Shrinkage by Λ

^{7}Li(π^+,K$^+$)$^{7}_{\Lambda}$Li
KEK E419
γ-ray spectroscopy
Hyperball Ge array

K. Tanida et. al.,
Phys. Rev. Lett. ***86****, 1982 (2001)*

E. Hiyama et. al.,
Phys. Rev. C ***59****, 2351 (1999)*

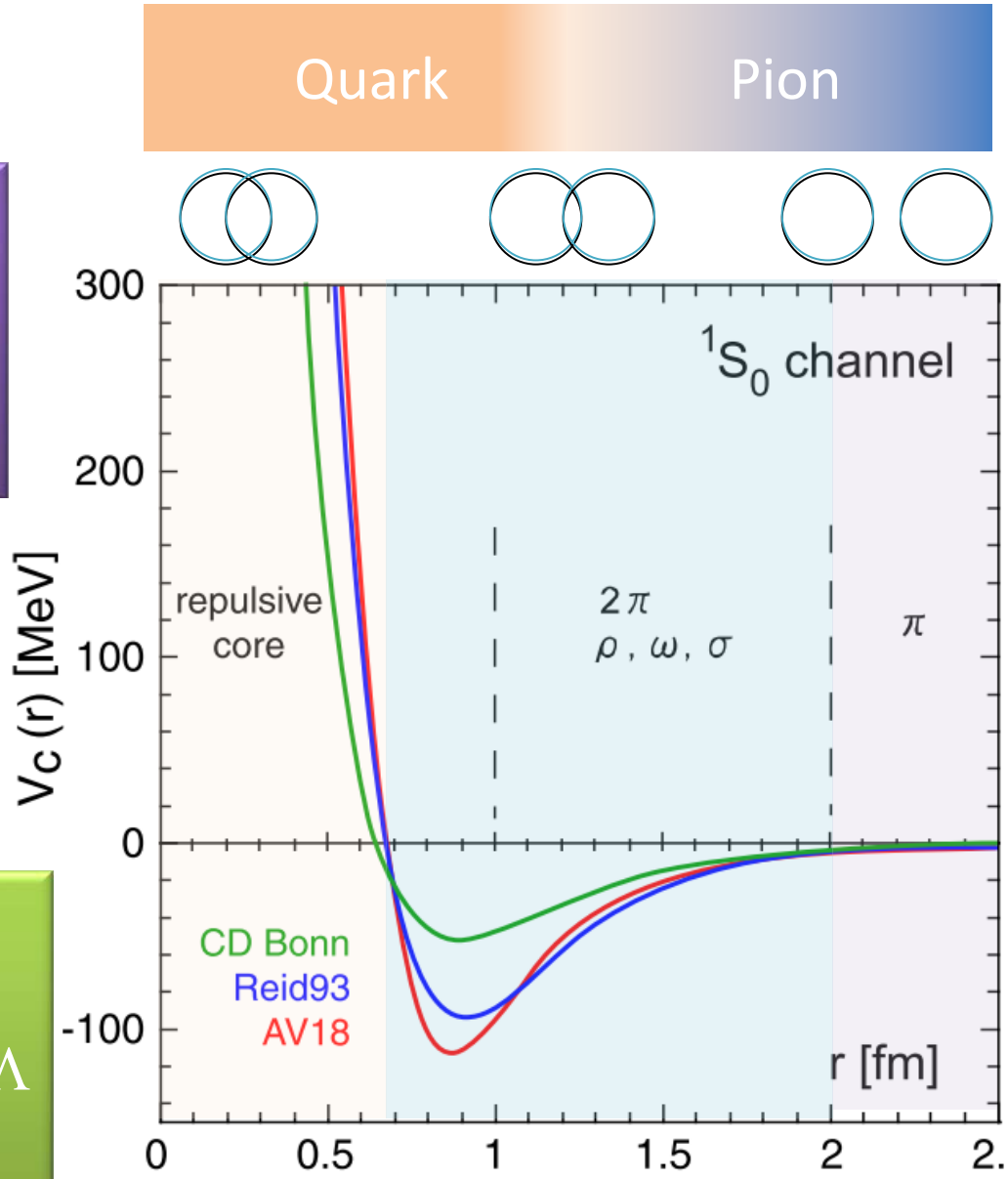
γ-ray spectroscopy of hypernuclei
～the ΛN interaction～

Nuclear force

Unified understanding
NN to full $SU_f(3)$ baryon-baryon interaction
•NN, YN, YY

Lack of NY and YY scattering data without hyperon beams

Investigations via hypernuclear properties
Λ hypernuclei $\rightarrow \Lambda N, \Sigma N, \Lambda\Lambda$
Ξ hypernuclei $\rightarrow \Xi N$
(J-PARC)



N. Ishii, S. Aoki, T. Hatsuda
Phys. Rev. Lett. 99, 022001 (2007)

ΛN spin-dependent interaction

Two-body effective ΛN interaction

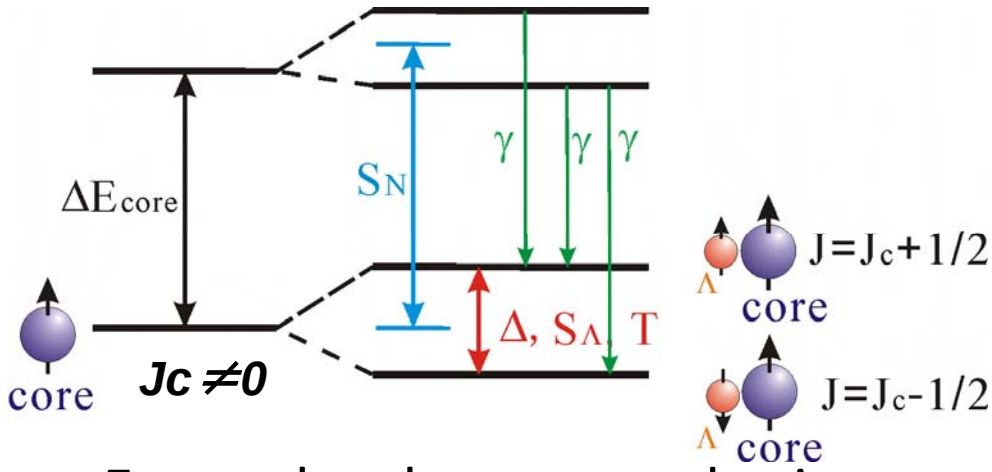
$$V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\,\vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\,\vec{l}_{\Lambda N}\vec{s}_\Lambda + V_N(r)\,\vec{l}_{\Lambda N}\vec{s}_N + V_T(r)\,S_{12}$$

Δ S_Λ S_N T

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

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

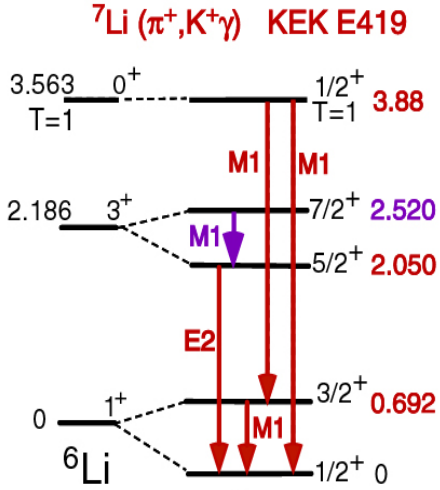
Δ: spin-spin
S_Λ, S_N : spin-orbit
T : Tensor



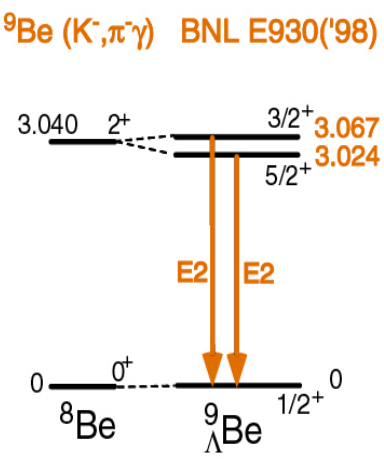
Energy levels expressed using these parameters from shell model (weak coupling limit)

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

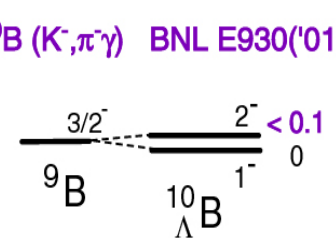
As of 2010



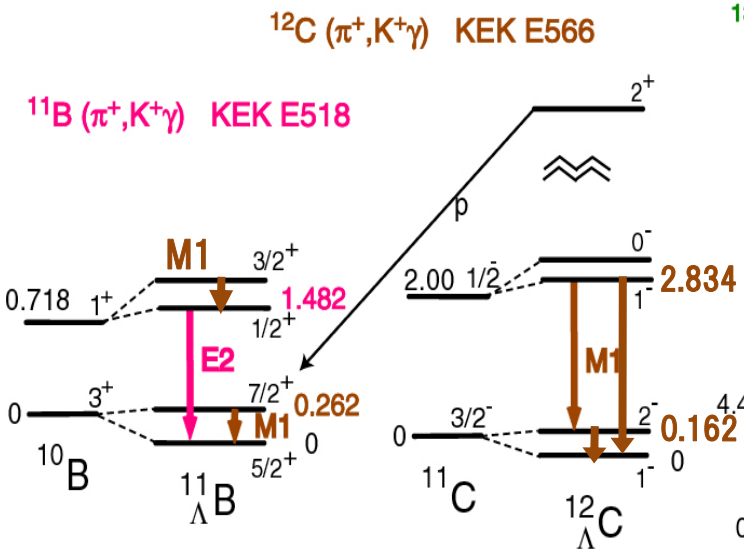
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



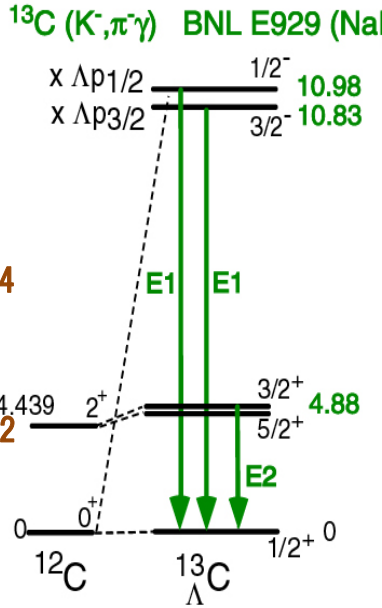
PRL 88 (2002) 082501
NPA 754 (2005) 58c



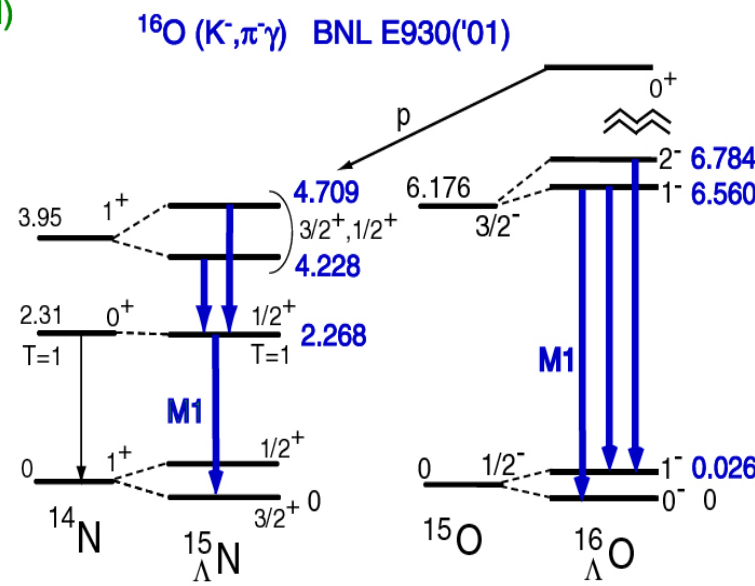
NPA 754 (2005) 58c



NPA 754 (2005) 58c
Y. Ma, Ph.D Thesis (2009)



PRL 86 (2001) 4255
PRC 65 (2002) 034607



PRL 93 (2004) 232501

γ-ray spectroscopy of hypernuclei
～the experimental methods～

Hypernuclear γ-ray spectroscopy ultra high counting rate and back ground

- **Beam species: π, K**
  - **secondary hadron beam**
  - **Beam halo: ~15 cm**
- **Beam intensity : ~10^6 Hz(10^7)**
- **Target thickness: ~10 g/cm^2**
  - **Scattering particles from target**

- Compton scattering (~300keV)
- π^0 decay
  - $\Lambda \rightarrow n + \pi^0$
  - $K^- \rightarrow \pi^- + \pi^0$
  - $\pi^0 \rightarrow \gamma\ \gamma$
- High energy charged particle (~50Mev)
- Neutron scattering
  - Neutron edge

Ge detector

Single counting rate :
50kHz ~100kHz
(250kHz)

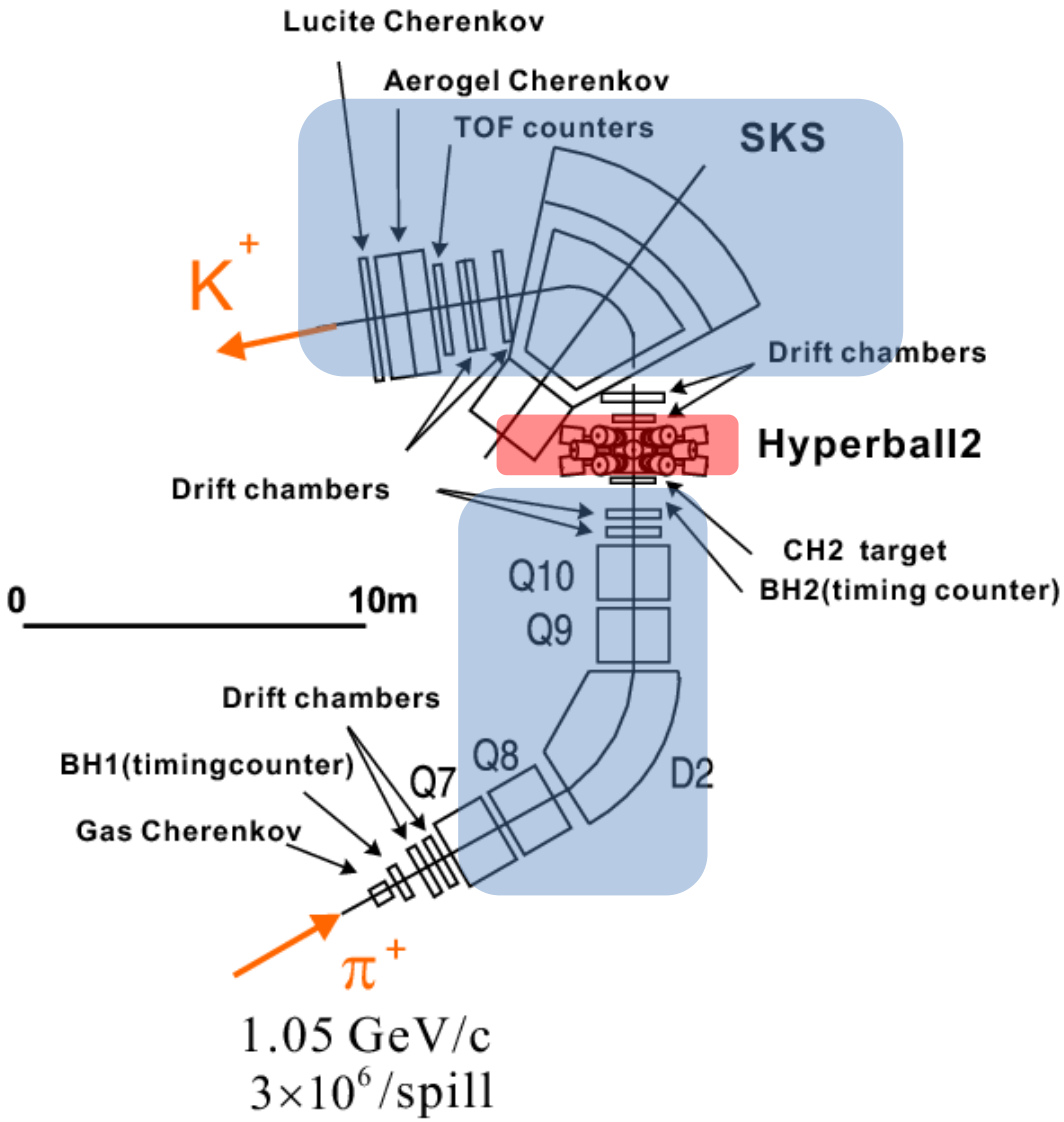
Energy deposit rate:
0.5TeV/s(2.5TeV/s)

A target
used in E566
$(CH_2)_n$ 18.6g/cm^2

E566 experimental setup

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

$^{11}_{\Lambda}B+p$

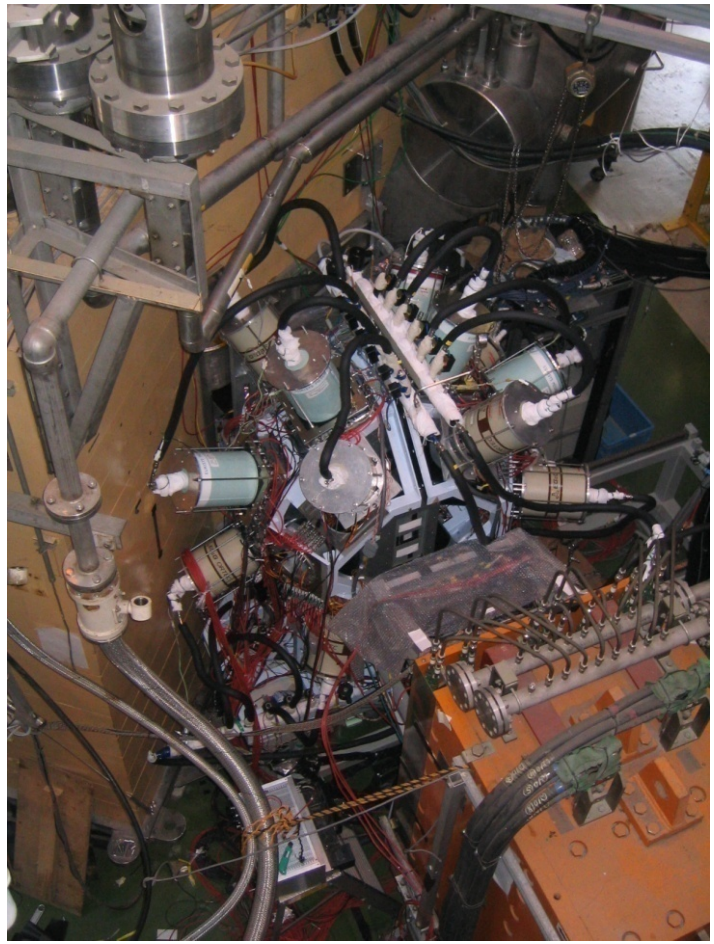


$BEAM = \overline{eGC} \otimes (TOF : BH1 \& BH2)$

$K^+ = Tof \otimes LC \otimes \overline{AC1} \otimes \overline{AC2}$

Hyperball 2

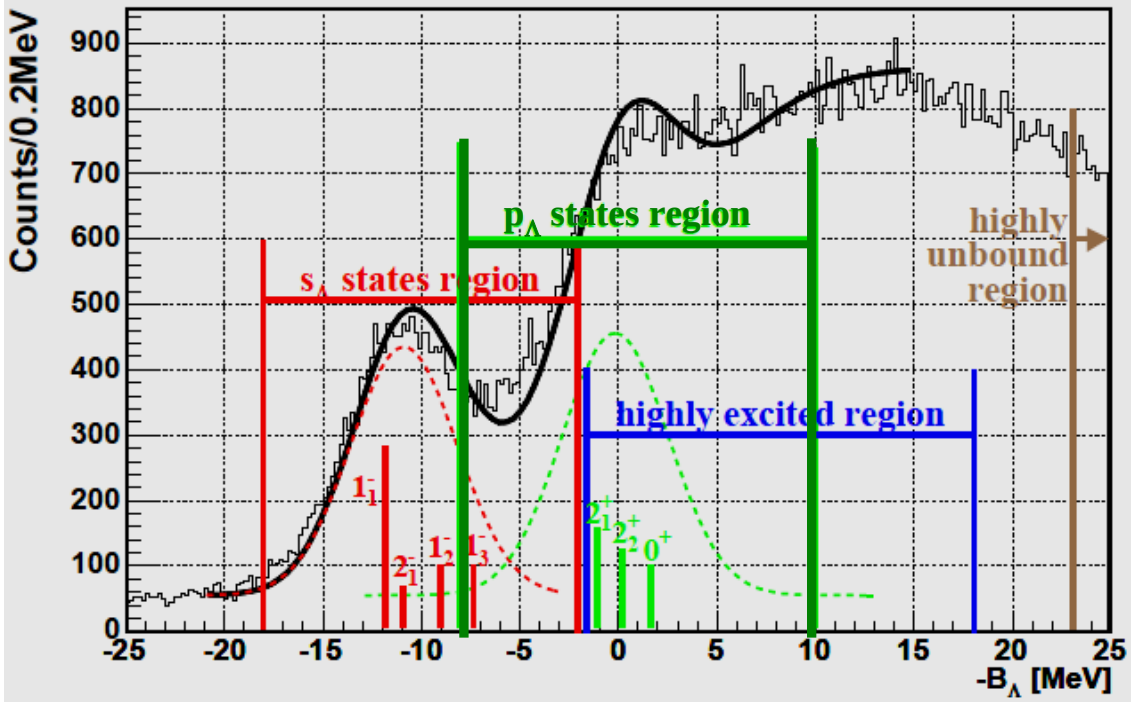
- KEK 12 GeV PS K6 beam line
- October, 2005
- $^{12}C(\pi^+, K^+)\ ^{12}_{\Lambda}C$ / $_{\Lambda}{}^{11}B+p$
- p_π=1.05GeV/c
- Target: $(CH_2)_n$ 18.6g/cm^2
- Trigger: $\pi^+K^+= BEAM \otimes K^+$
- Intensity:
  - $3x10^6$/spill
  - $2x10^{12}$ (total π^+)
- Reaction spectrometers: K6/SKS
- γ-ray detector: Hyperball2

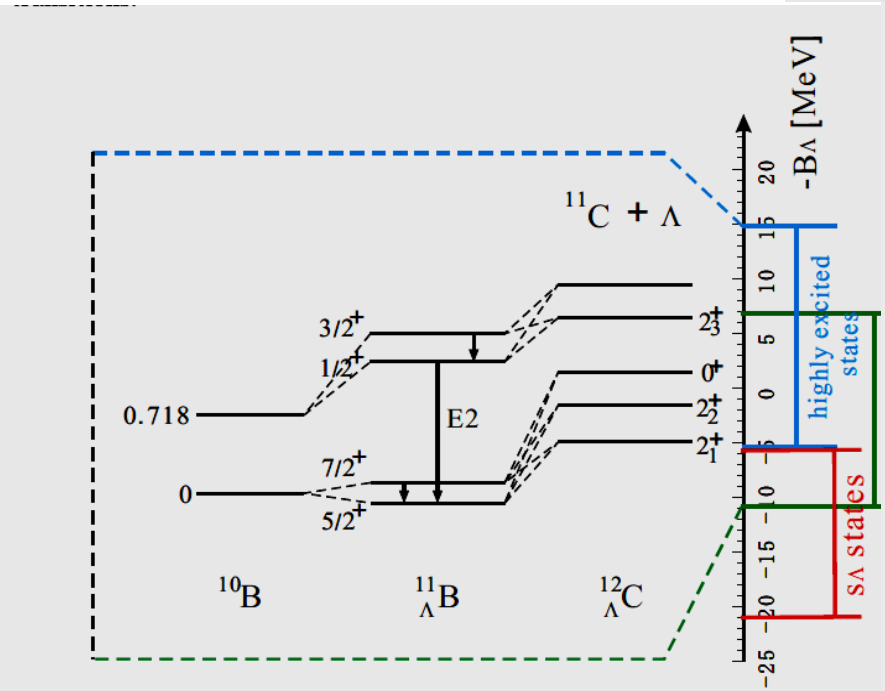


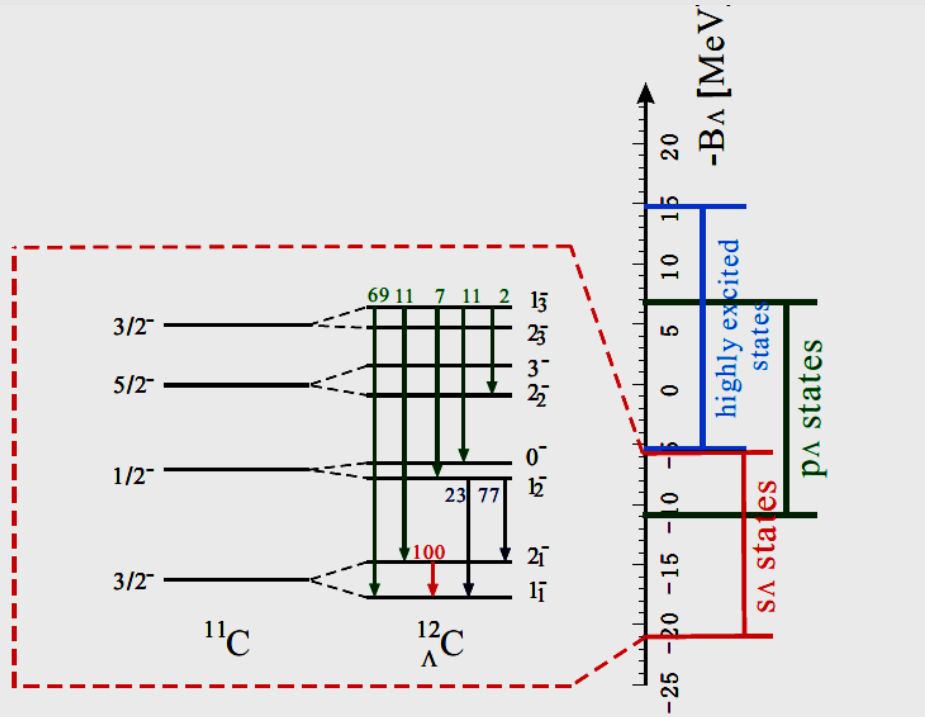
Hyperball2 at KEK 2005
E566: last experiment at KEK PS

Missing mass spectrum and selection of states

Y. Ma, Ph.D thesis (2009) , Tohoku Univ.







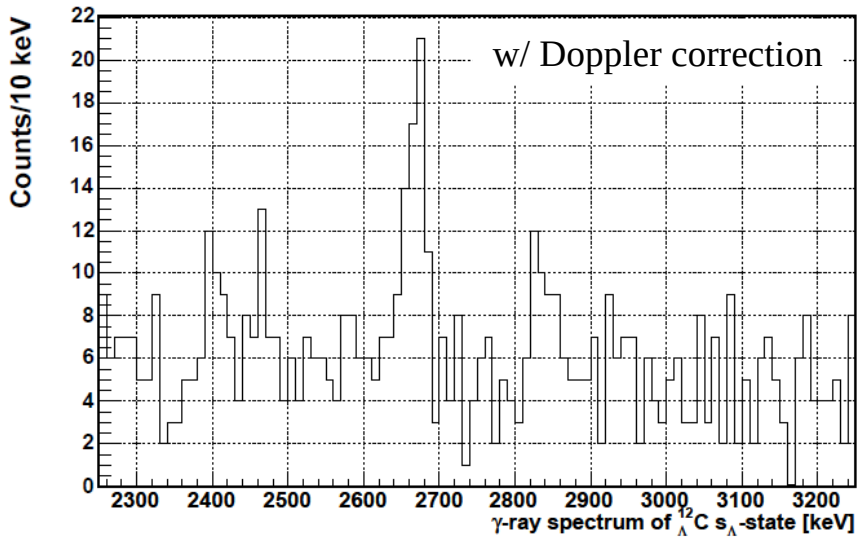
Assignment of γ in $^{12}_{\Lambda}C$

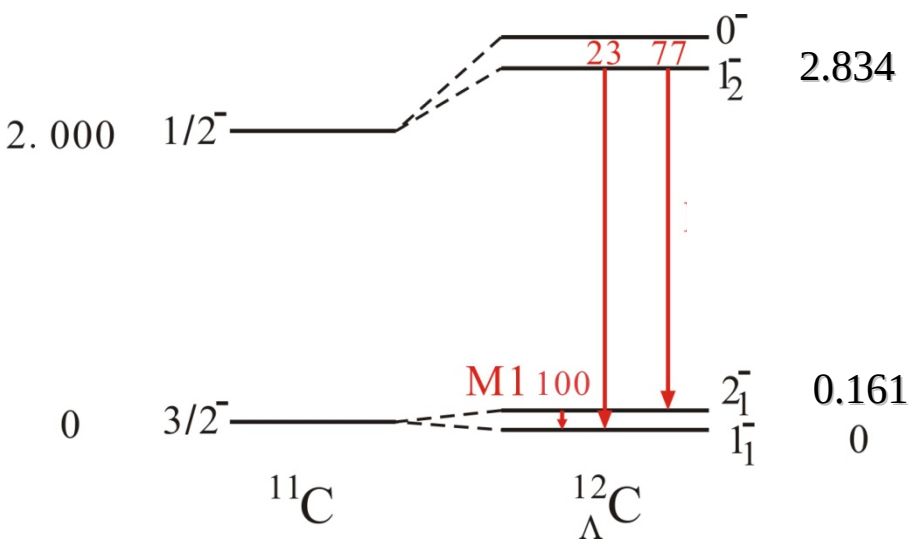
3 γ rays coincident with the s_Λ region

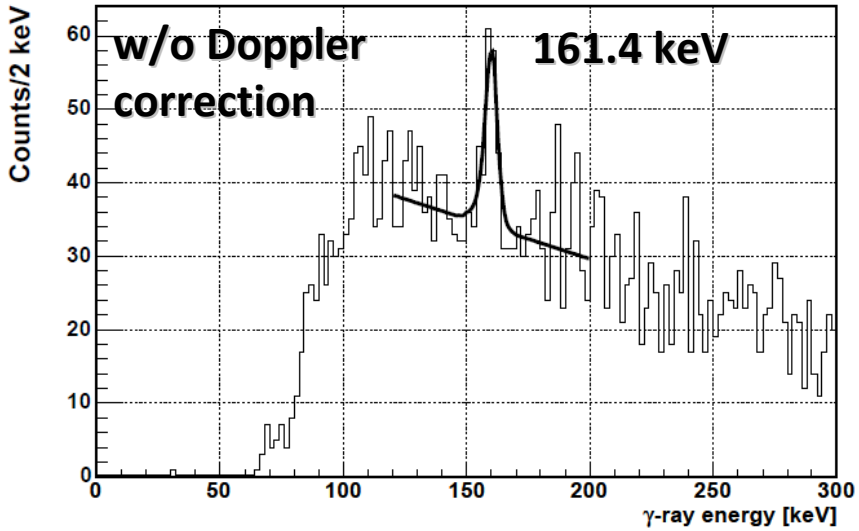
$E_\gamma(1_2^- \rightarrow 1_1^-) = 2833.9 \pm 5.6 \pm 0.3 keV$

$E_\gamma(1_2^- \rightarrow 2_1^-) = 2670.2 \pm 2.6 \pm 0.3 keV$

$E_\gamma(2_1^- \rightarrow 1_1^-) = 161.4 \pm 0.7 \pm 0.3$ keV







Assignment of γ in $^{11}_{\Lambda}$B

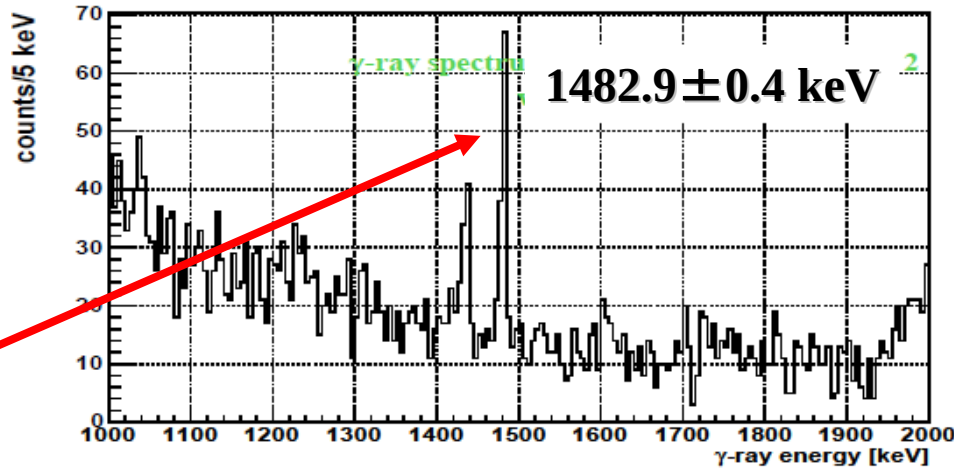
3 γ rays coincident with the p_Λ region

$E_\gamma(7/2^+ \rightarrow 5/2^+) = 262.9 \pm 0.2\ ^{+0.4}_{-0.0}$ keV

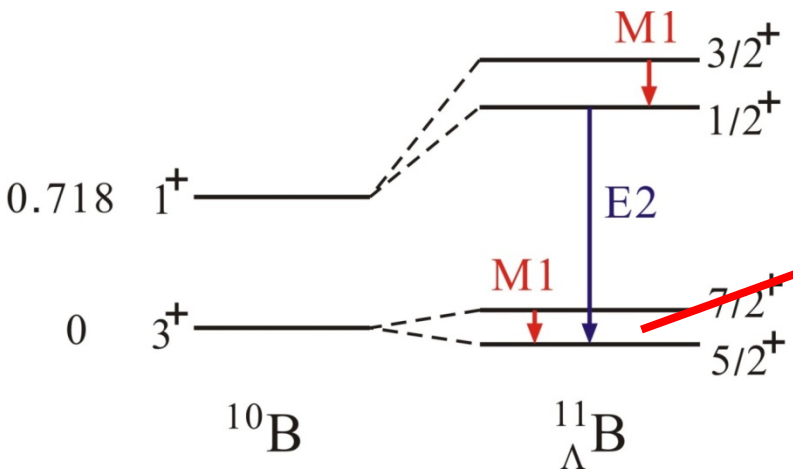
$E_\gamma(1/2^+ \rightarrow 5/2^+) = 1482.9 \pm 0.4 \pm 0.2$ keV

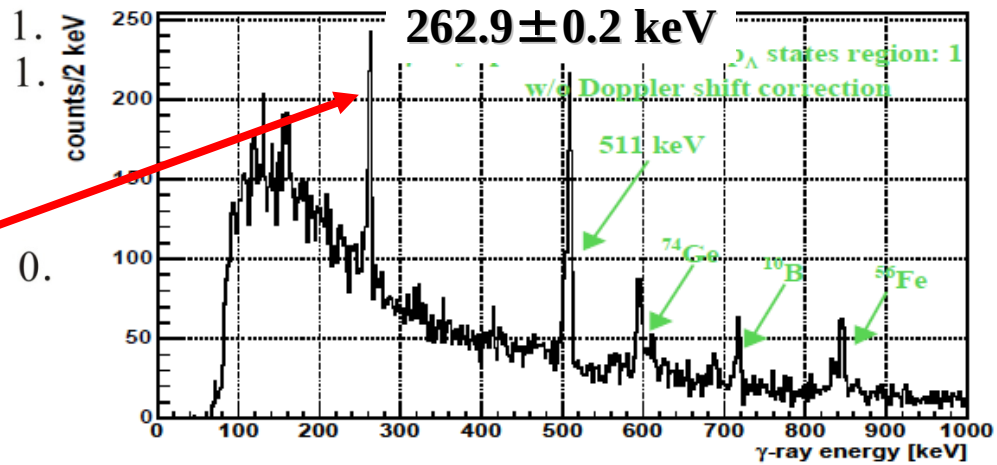
$E_\gamma(3/2^+ \rightarrow 1/2^+) = 503.9 \pm 0.7 \pm 0.2$ keV

observed in KEK-E518:
^{11}B(π^+, K$^+$) $^{11}_{\Lambda}$B



Gate on p_Λ region
w/o Doppler correction



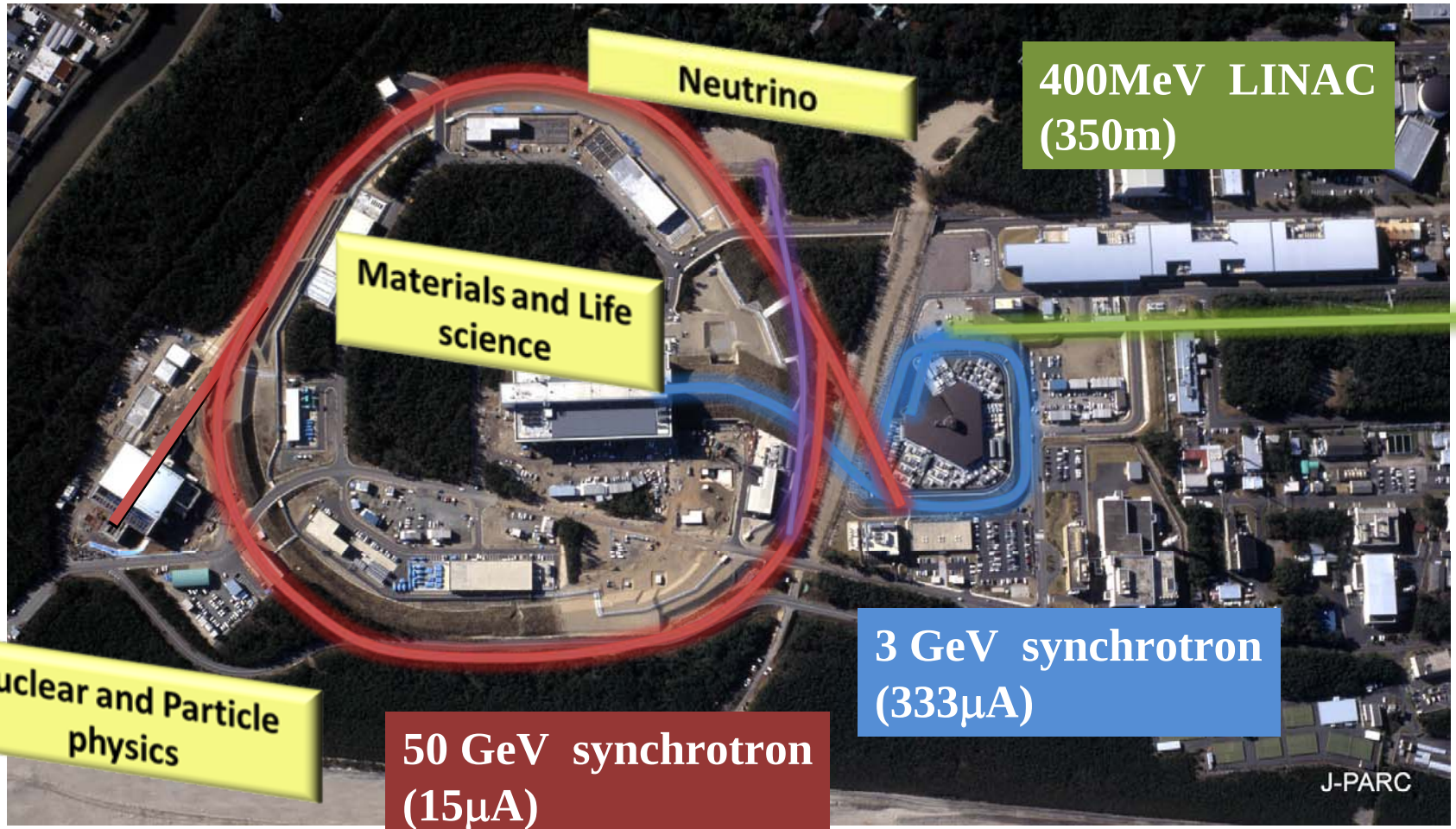


- Thick target
  - Cannot use an enriched target -> limited number of targets
  - So far only DSAM to measure lifetimes
- γ-γ coincidence not yet a standard
- Experimental determination of spin and parity from γ-ray transitions yet to be performed
- Use of PMTs for ACS in fringing fields of a magnet
  - Heavy shielding required

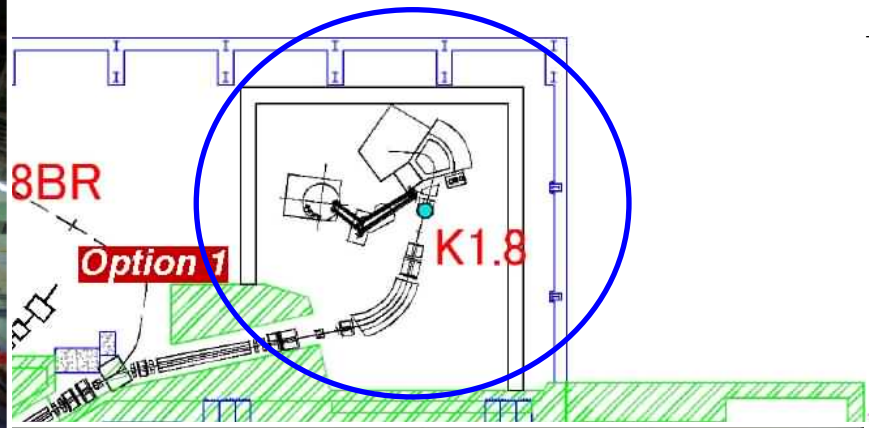
- Reaction-γ coincidence
  - event by event reconstruction of reaction kinematics
  - reaction point and recoil velocity information

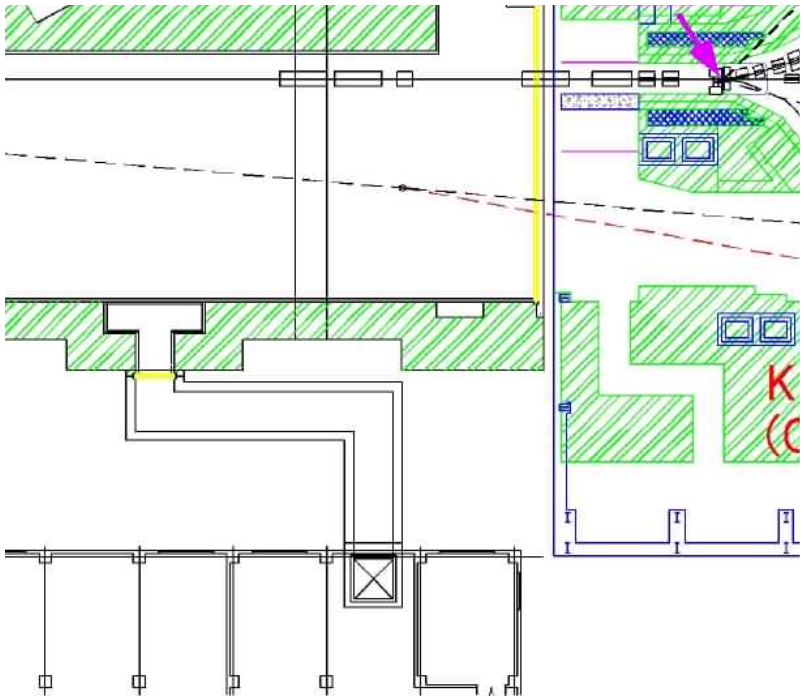
J-PARC and Hyperball-J
～the E13 experiment～

Japan Proton Accelerator Research Complex (J-PARC)


Neutrino
400MeV LINAC
(350m)
Materials and Life
science
Nuclear and Particle
physics
3 GeV synchrotron
(333μA)
50 GeV synchrotron
(15μA)
J-PARC

dron Hall


8BR
Option 1
K1.8

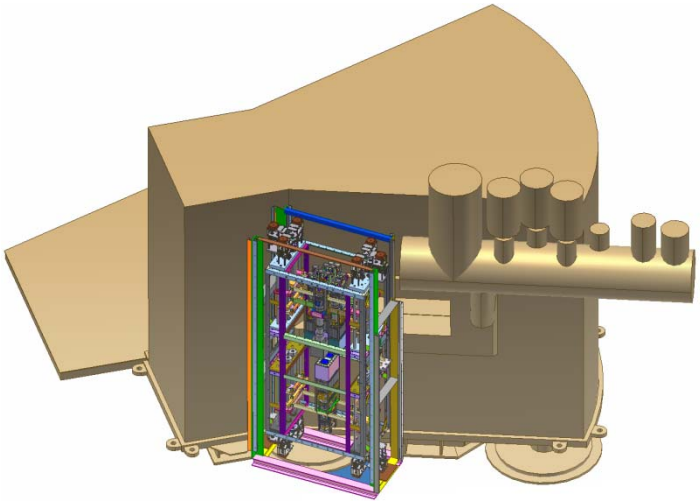



祝ハドロンビームライン
ビーム取り出し・輸送成功
平成21年1月27日 19時35分

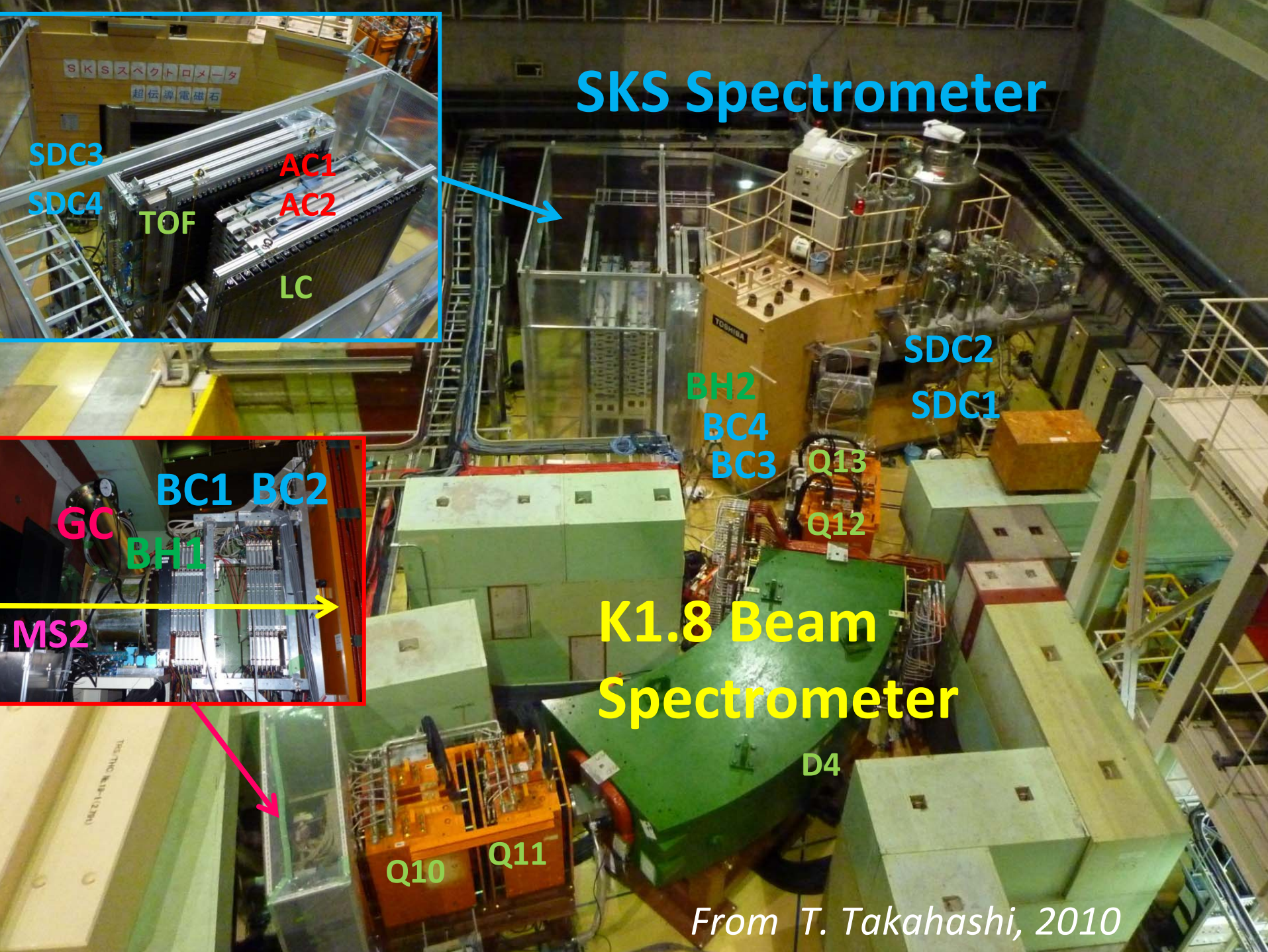
J-PARC E13 experimental setup

(K^-, π^-) reaction @ p_K = 1.5 GeV/c

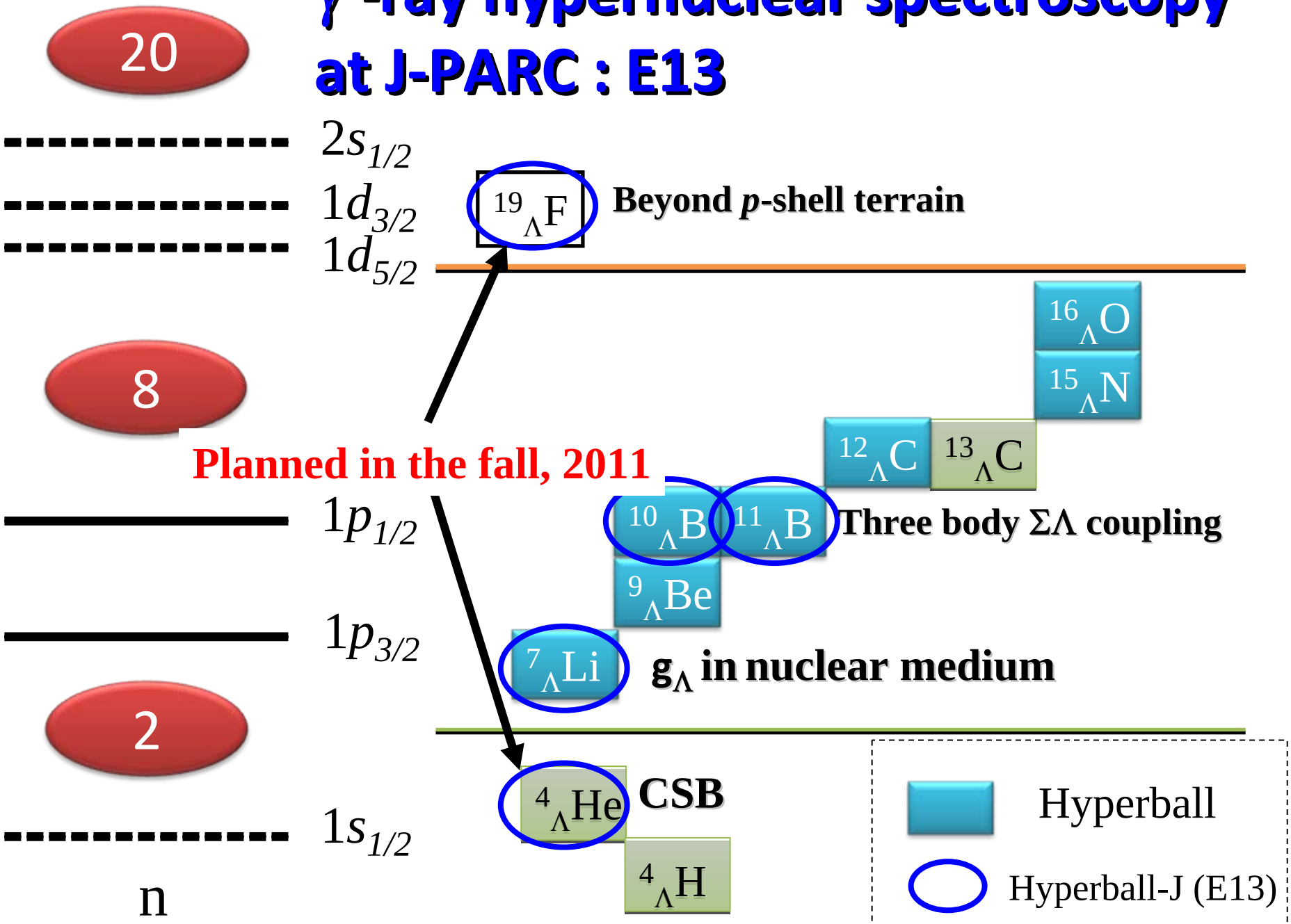
SKS spectrometer
SksMinus



Beam line spectrometer


SKS Spectrometer
SDC3
SDC4
TOF
AC1
AC2
LC
SDC2
SDC1
BH2
BC4
BC3
Q13
Q12
BC1
BC2
GC
BH1
MS2
K1.8 Beam
Spectrometer
D4
Q10
Q11
From T. Takahashi, 2010

γ -ray hypernuclear spectroscopy at J-PARC : E13



The Ge array: Hyperball-J

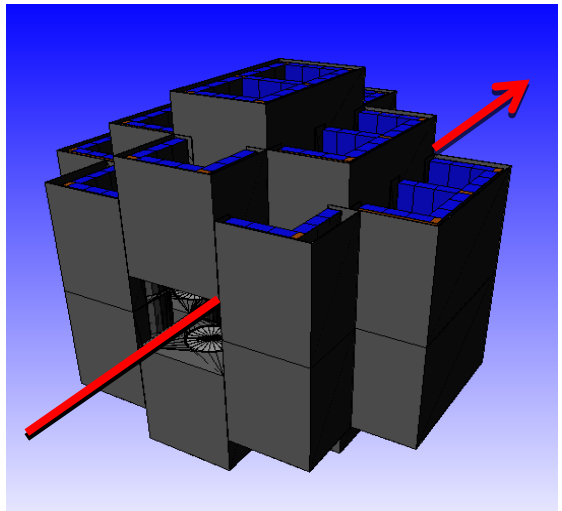
Total budget ～3M USD

Designed started in 2005

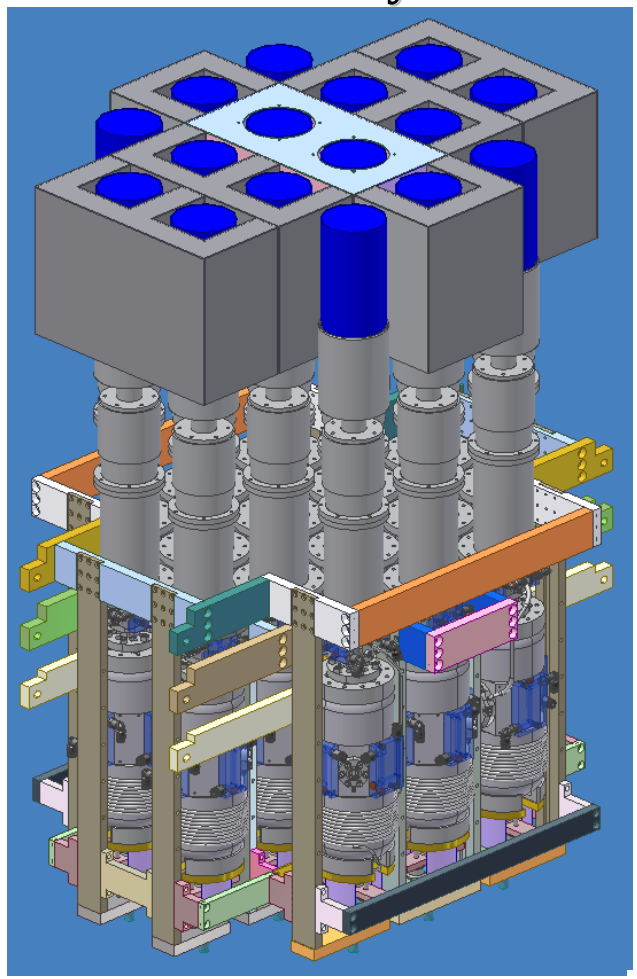
Graduate students as a main work force

Hyperball-J Ge array

- Compact arrangement
- Ge detector x32 (full set)
- Total photo peak eff. ~6% for 1-MeV γ ray
- High modularity
- Adjustable geometry
- Remotely controlled
- Radiation hardness
- Fast background suppression
- Pile up separation and baseline restration



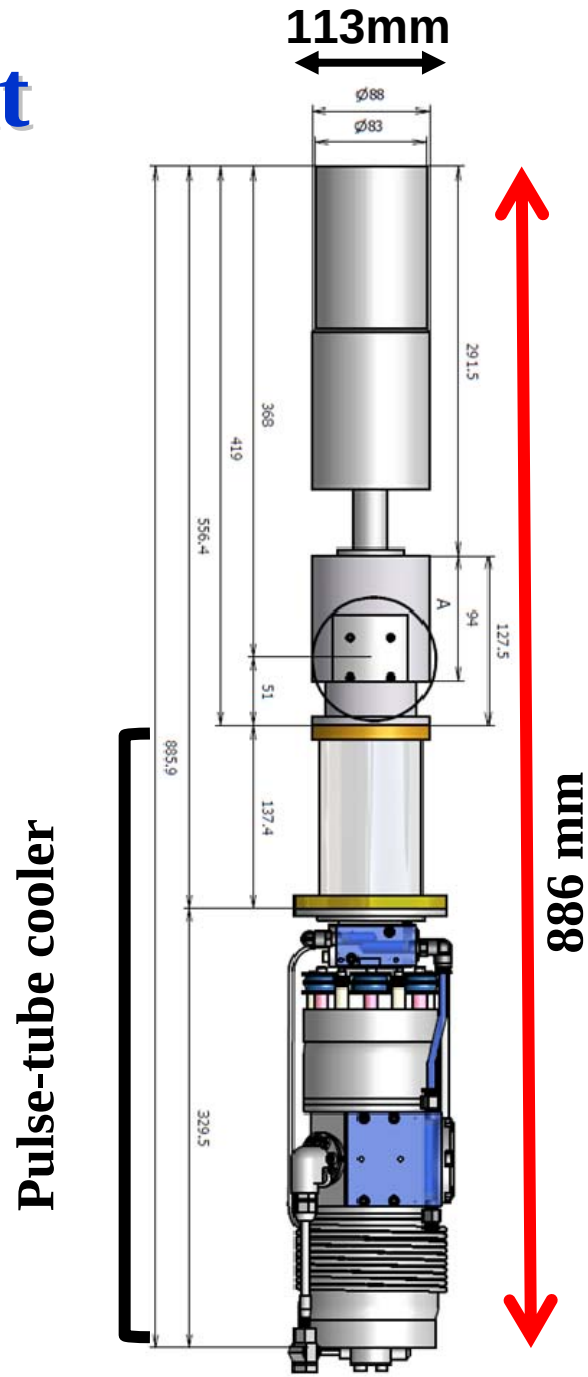
Half the array shown



Planar arrangement

HBJ detector unit

- N-type
- Relative eff. 60%
- Transistor reset type
  - 150MeV/reset
  - 20～50mV/MeV
- Pulse Tube Cooling
  - crystal temp. :~70K
  - Radiation hardness
- Temperature monitored on line
  - Bias shutdown
  - Gain correction



Ge det. unit: performance

Ge sensor
(Transplantable)

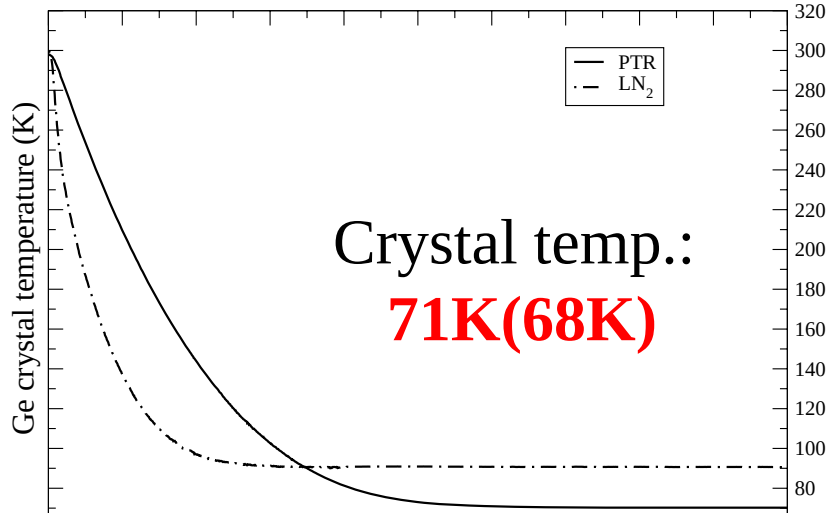
Cold head

Pulse tube

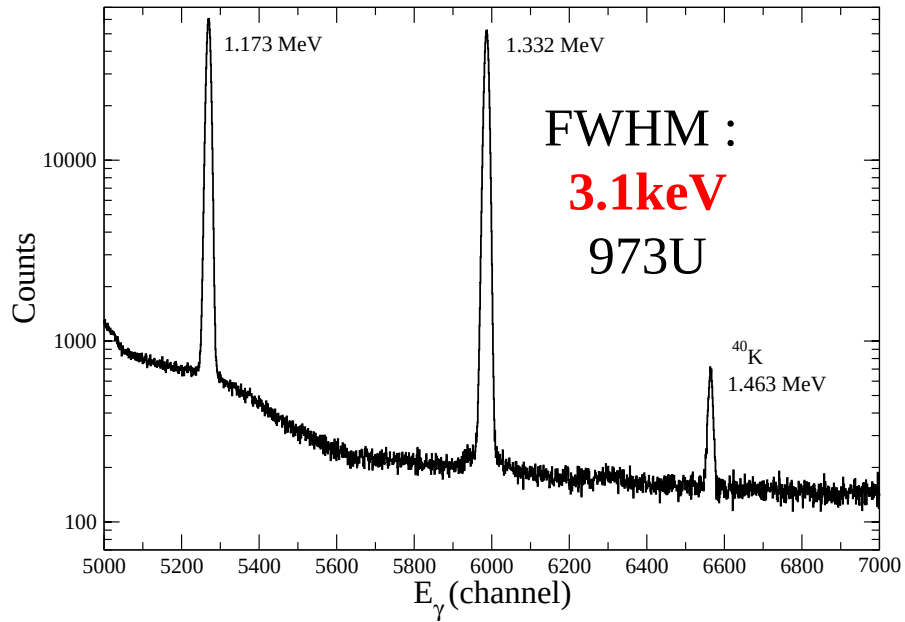
Stirling
compressor

Water
cooling

114mm

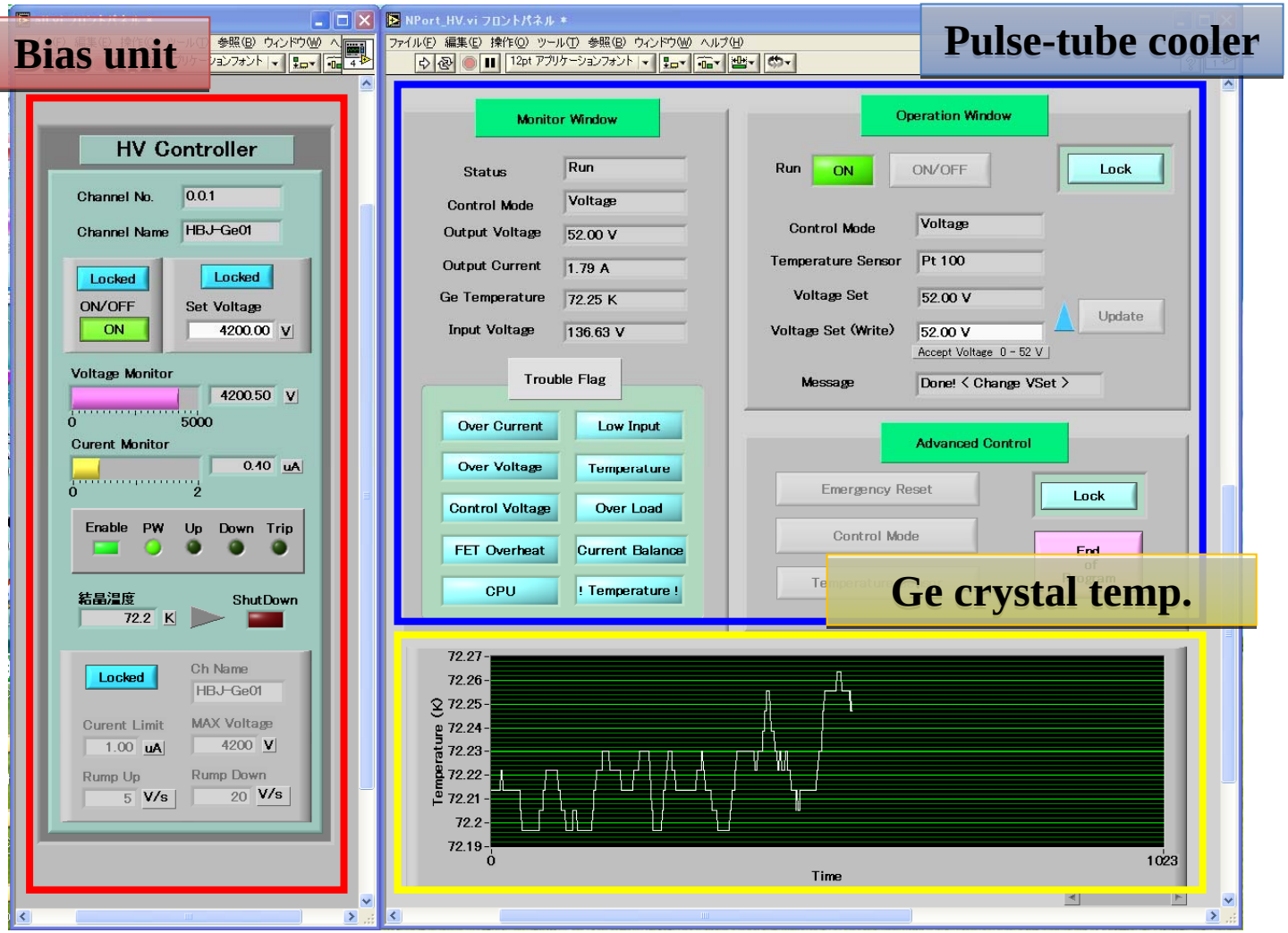


Crystal temp.:
71K(68K)



FWHM :
3.1keV
973U

Control display (for a single detector)



Background events in hypernuclear γ-ray spectroscopy

Energy<1MeV

- Compton scatter

Energy >10MeV

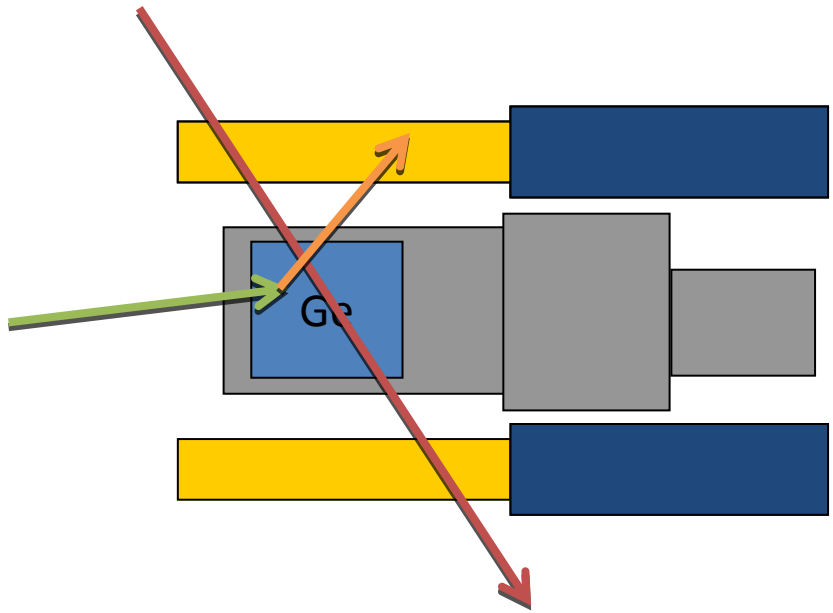
- π^0 decay

  $\Lambda \rightarrow n + \pi^0$

  $K^- \rightarrow \pi^- \pi^0$

  $\pi^0 \rightarrow \gamma\ \gamma$

- High energy charged particle



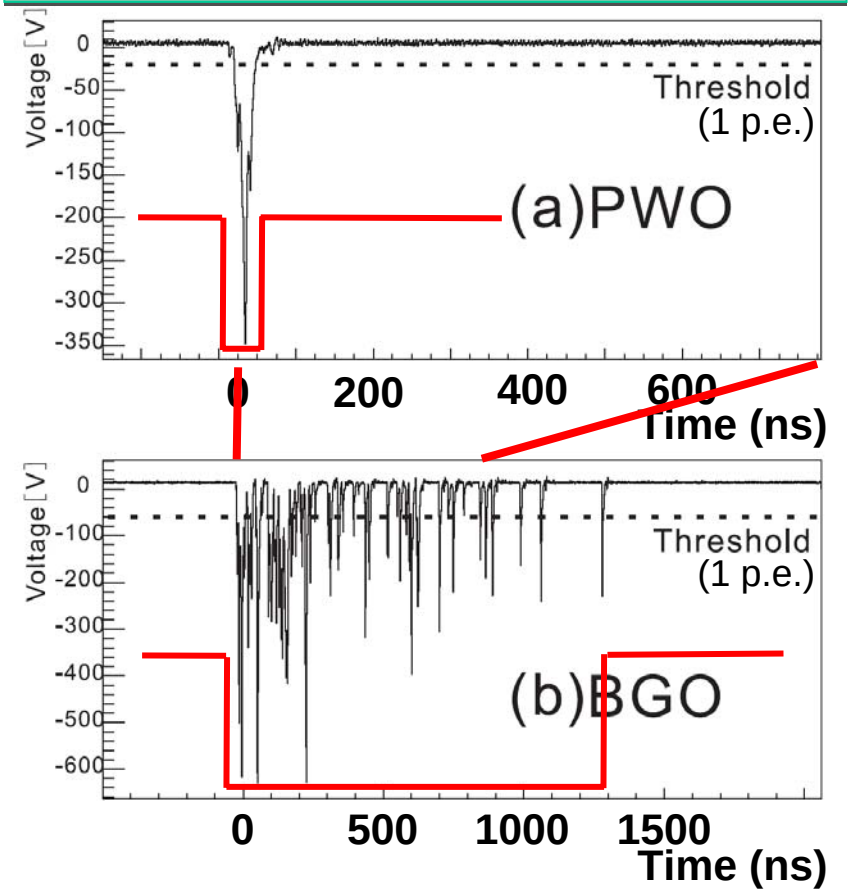
Compton & background suppression by PWO crystals

Conventional BGO counters

PWO($PbWO_4$) counters

Crystal	BGO	**PWO**
Effective atomic number	75	**76**
Density [g/cm^3]	7.23	**8.28**
Decay constant [ns]	300	**~6**
Radiation length	1.12	**0.86**
Light yield [NaI=100]	15	**~1**

Typical pulse shape for 661 keV



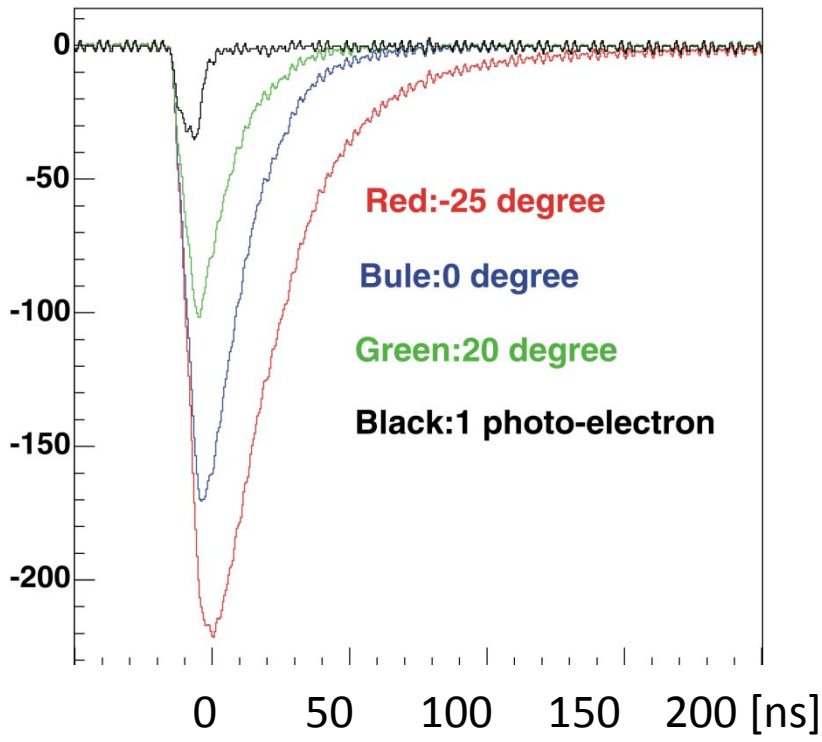
Never used for low energy nuclear γ

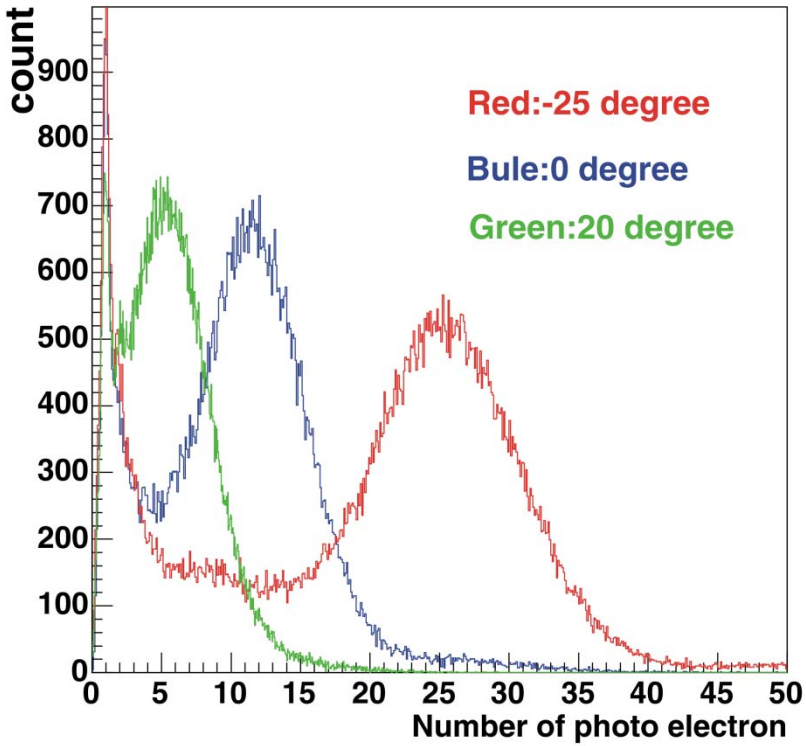
To increase light yield

- Doping
- Cooling

Results of measurements

Average waveform





Height and width of a signal changes with temperature.

Number of photo electron for 661-keV γ ray

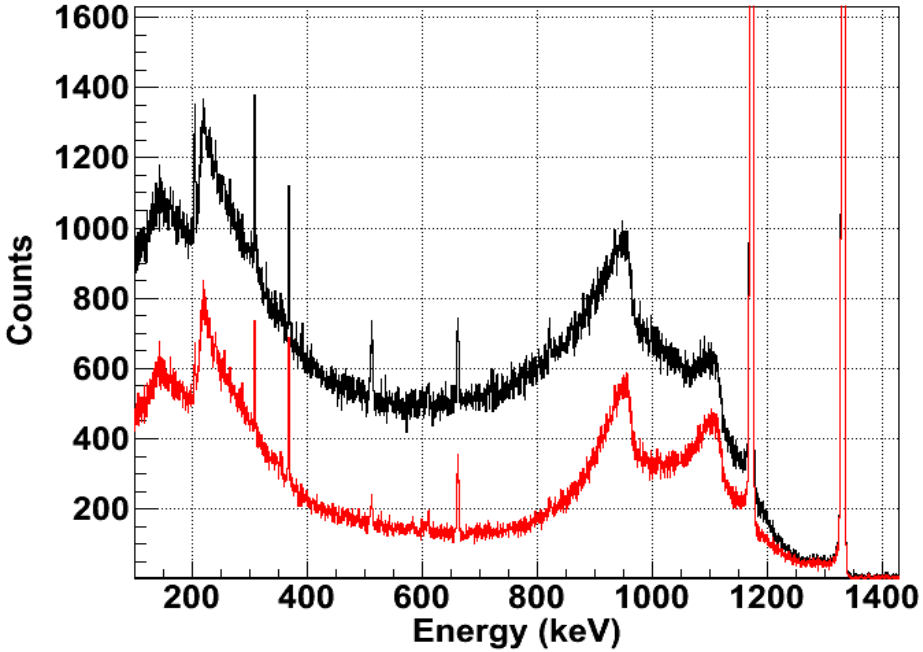
20°C→6.0

0°C→11.5

-25°C→25.8

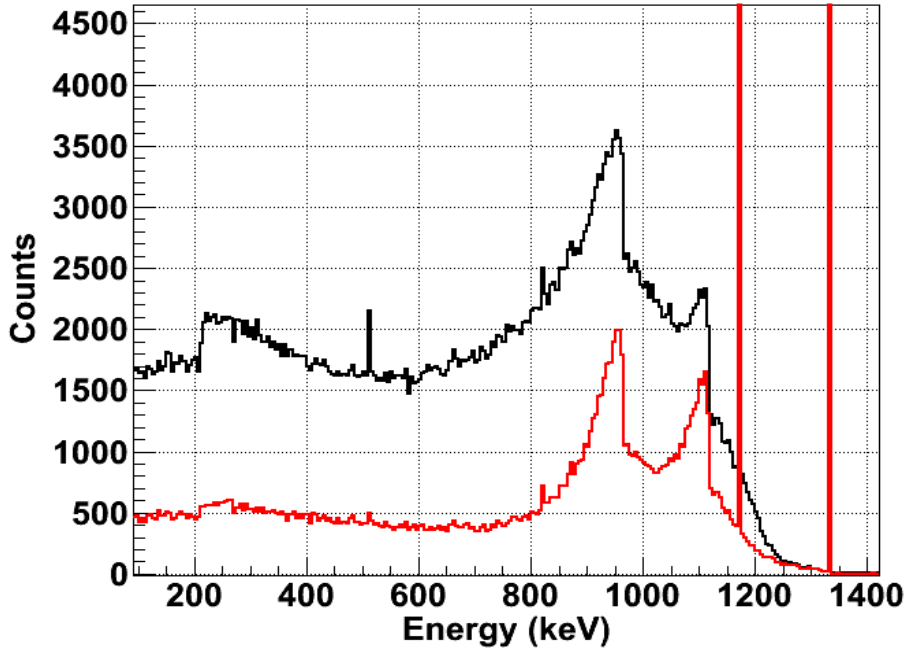
PWO suppression performance

Measurement at -20 deg.



>100 keV	0.19	0.33
>500 keV	0.31	0.49

Simulation

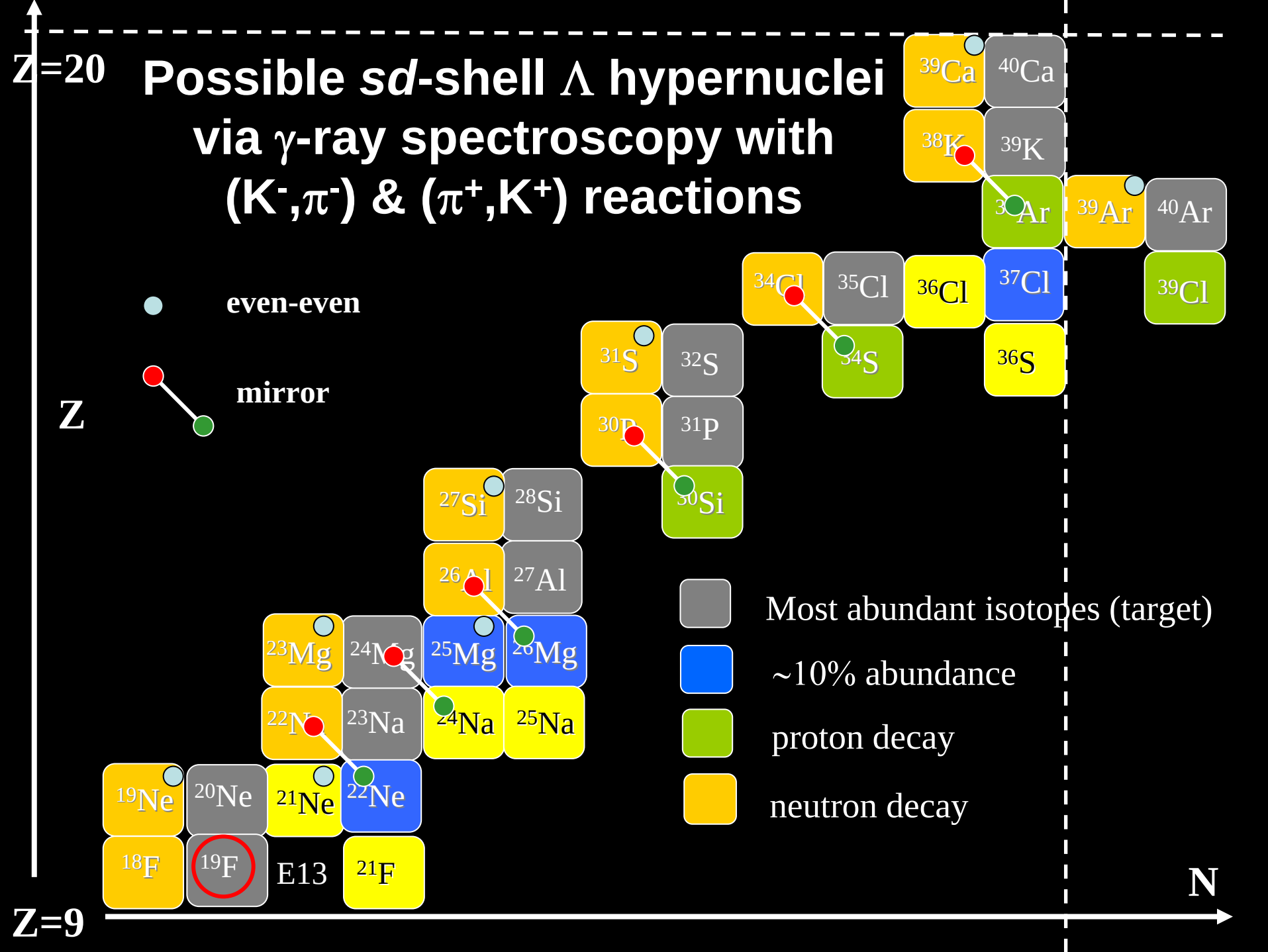


>100 keV	0.26	0.51
>500 keV	0.35	0.59

Tohoku University, 2010

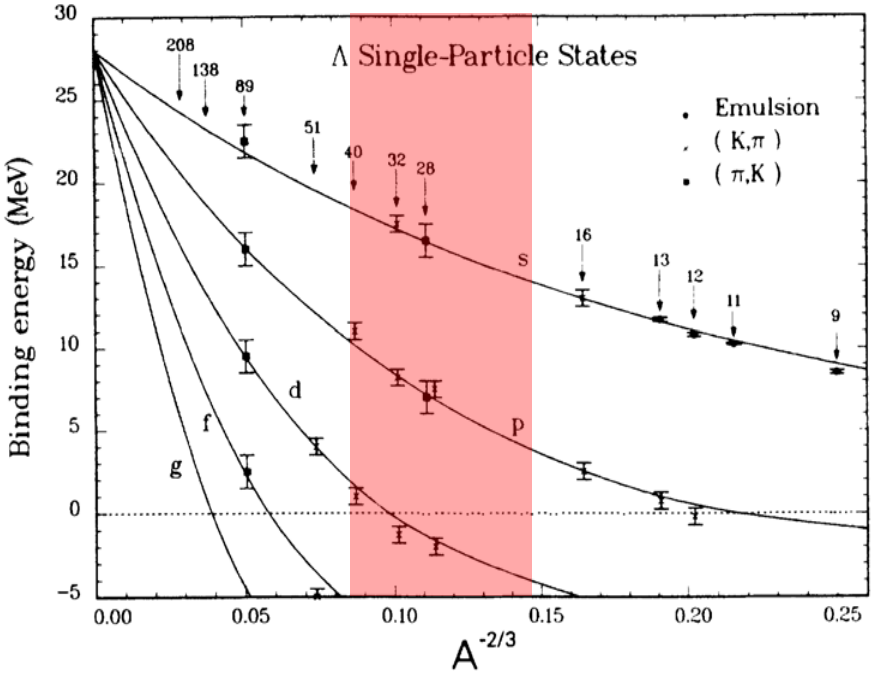
sd-shell hyprenuclei

~ $^{25}_{\Lambda}$Mg ~


Z=20
Possible sd-shell Λ hypernuclei via γ-ray spectroscopy with (K-,π-) & (π+,K+) reactions
even-even
mirror
Z
N
Z=9
39Ca
40Ca
38K
39K
39Ar
40Ar
34Cl
35Cl
36Cl
37Cl
39Cl
31S
32S
34S
36S
30P
31P
30Si
27Si
28Si
26Al
27Al
23Mg
25Mg
26Mg
22Ne
23Na
24Na
25Na
19Ne
20Ne
21Ne
22Ne
18F
19F
E13
21F
Most abundant isotopes (target)
~10% abundance
proton decay
neutron decay

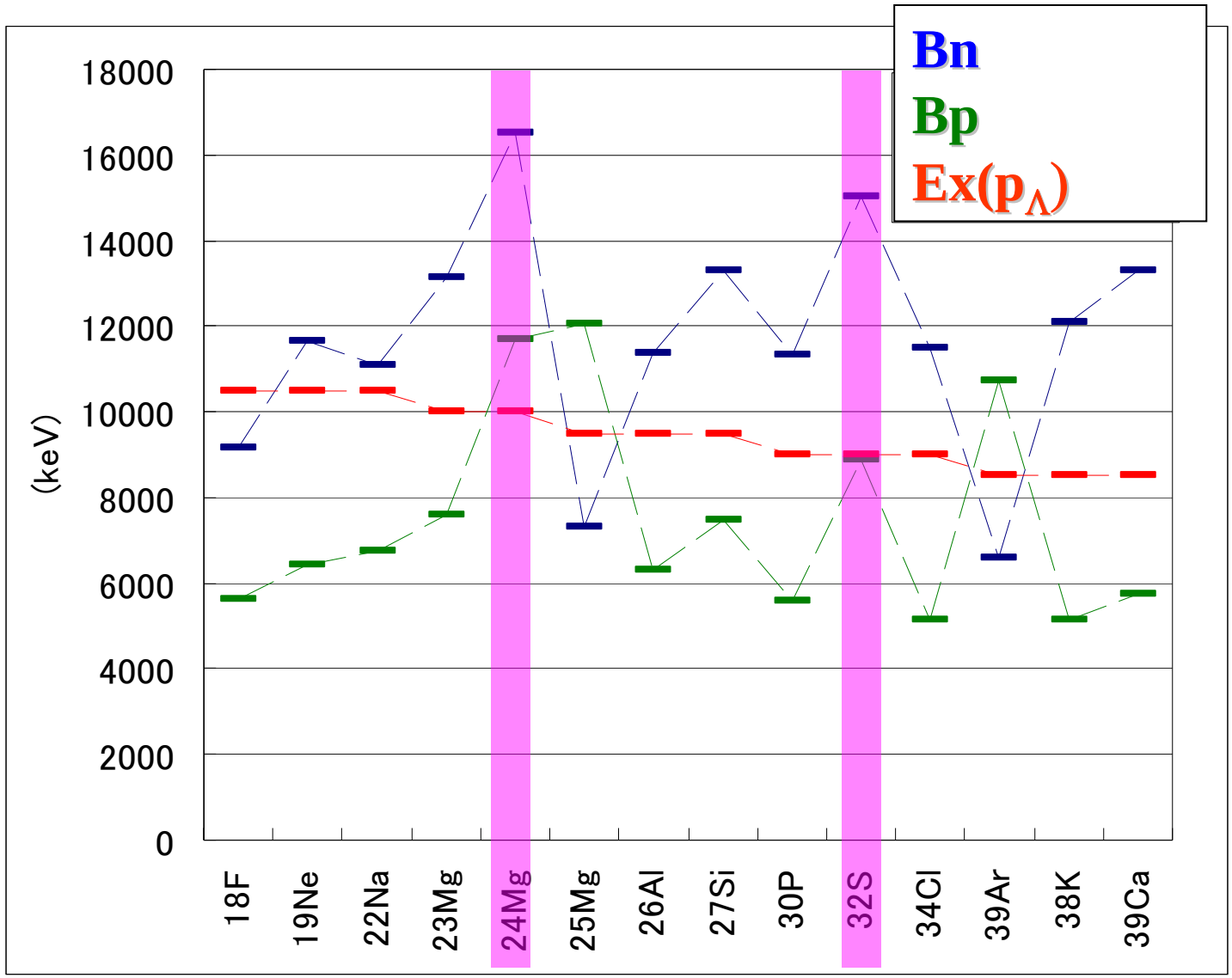
Bound states of *sd*-shell nuclei and hypernuclei

- Co-existence of shell (mean field) and cluster-like structures
- More valence nucleons
  - higher level densities (especially odd-odd)
- Collective (rotational) excitation spectrum → low-lying energy
- p_Λ states also bound

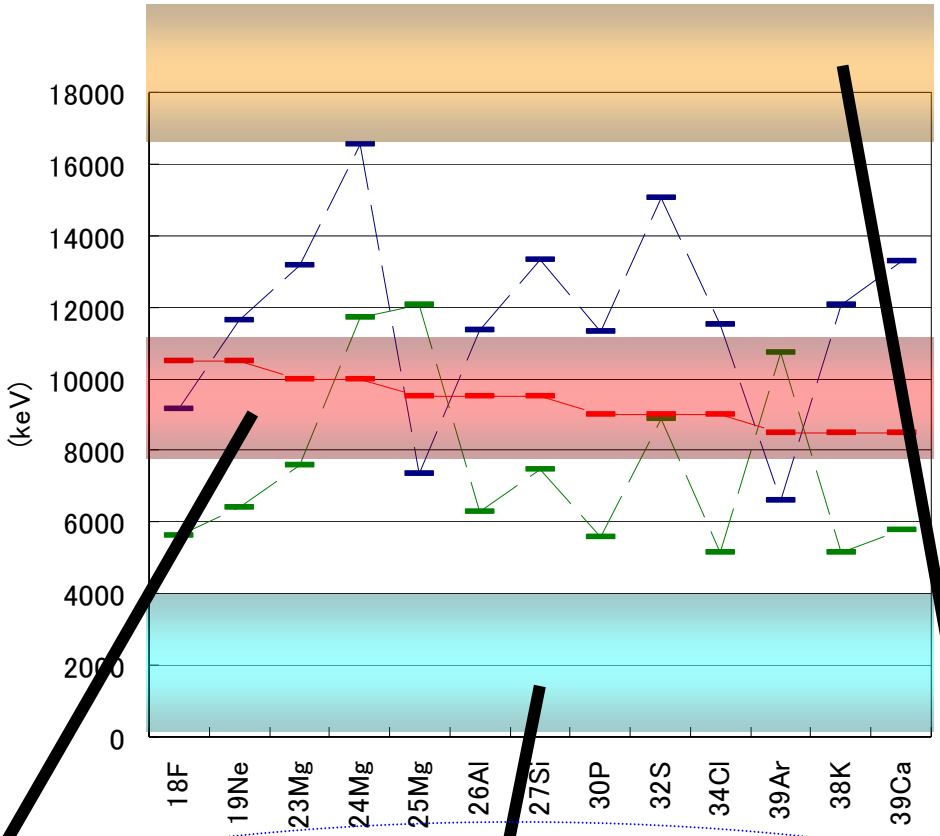


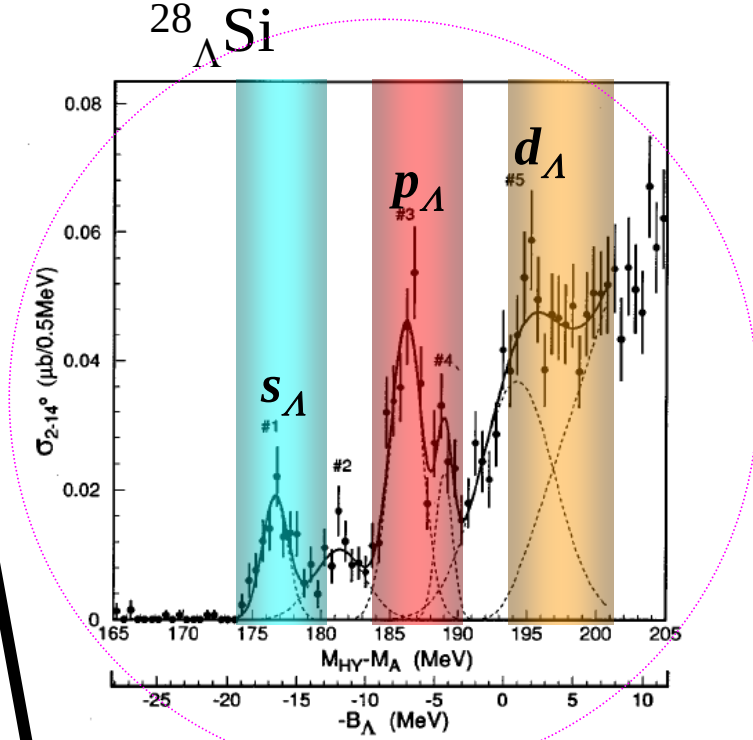
D. J. Millener *et al.*,
Phys. Rev. C, 38 2700 (1988)

- Shell model
- Cluster model
- Self-consistent calculations
  - RMF
  - Hatree-Fcok+BCS
- AMD



Target A -1Z_{n-1}





(π+,K+) T.Hasegawa et al., Phys. Rev. C 53, 1210 (1996)

SKS

γ γ γ

A-1ΛZ-1 AΛZ A-1ΛZ

γ-γ coincidence with Hyperball-J

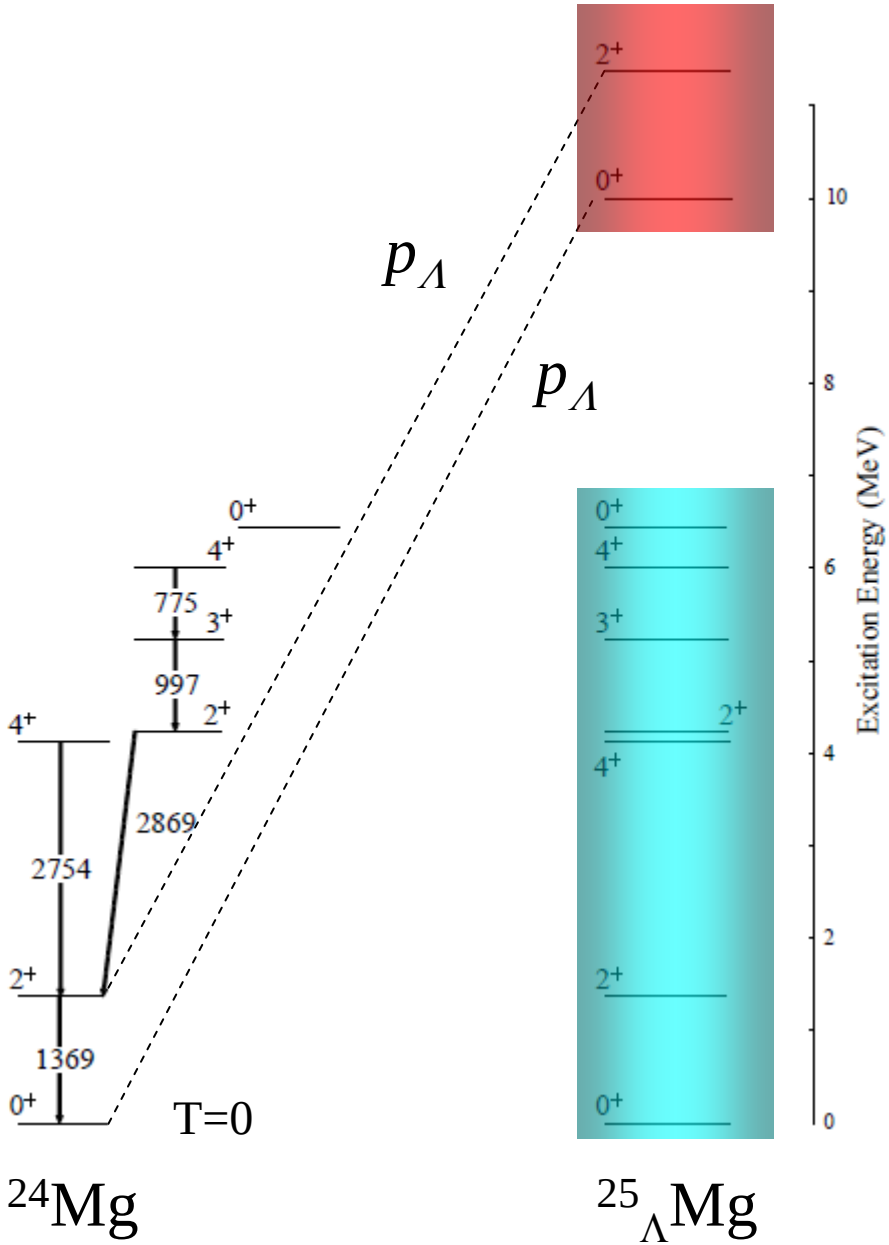
Weak decay

(mostly via non-mesonic in the *sd*-shell hypernuclei)

γ-ray spectroscopy of $^{25}_{\Lambda}$Mg

- Well deformed & even-even core hypernuclei
  - low and simple (regular) energy level
  - direct observation of core polarization effect of Λ
    - Nuclear density saturation at the g.s. with little change in size, but a shape can change in (β,γ) plane
    - A few 100 keV change
    - Observation of spin averaged 2_1^+, 2_2^+, $0_2^+ \rightarrow (\beta,\gamma)$
    - Observation of 4_1^+
- p_Λ-bound-states particle stable (Bp=11693keV Bn=16532 keV)
  - Observation of p_Λ splitting in the *sd*-shell
    - Hyperball-J with LaBr, CsI detectors (?)
- Use of a natural target
  - possibility of increasing the number of accessible hypernuclei
  - a test case for heavier hypernucley beyond *sd*-shell

^{24}Mg level scheme



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Hyperball-J collaboration

23 institutes