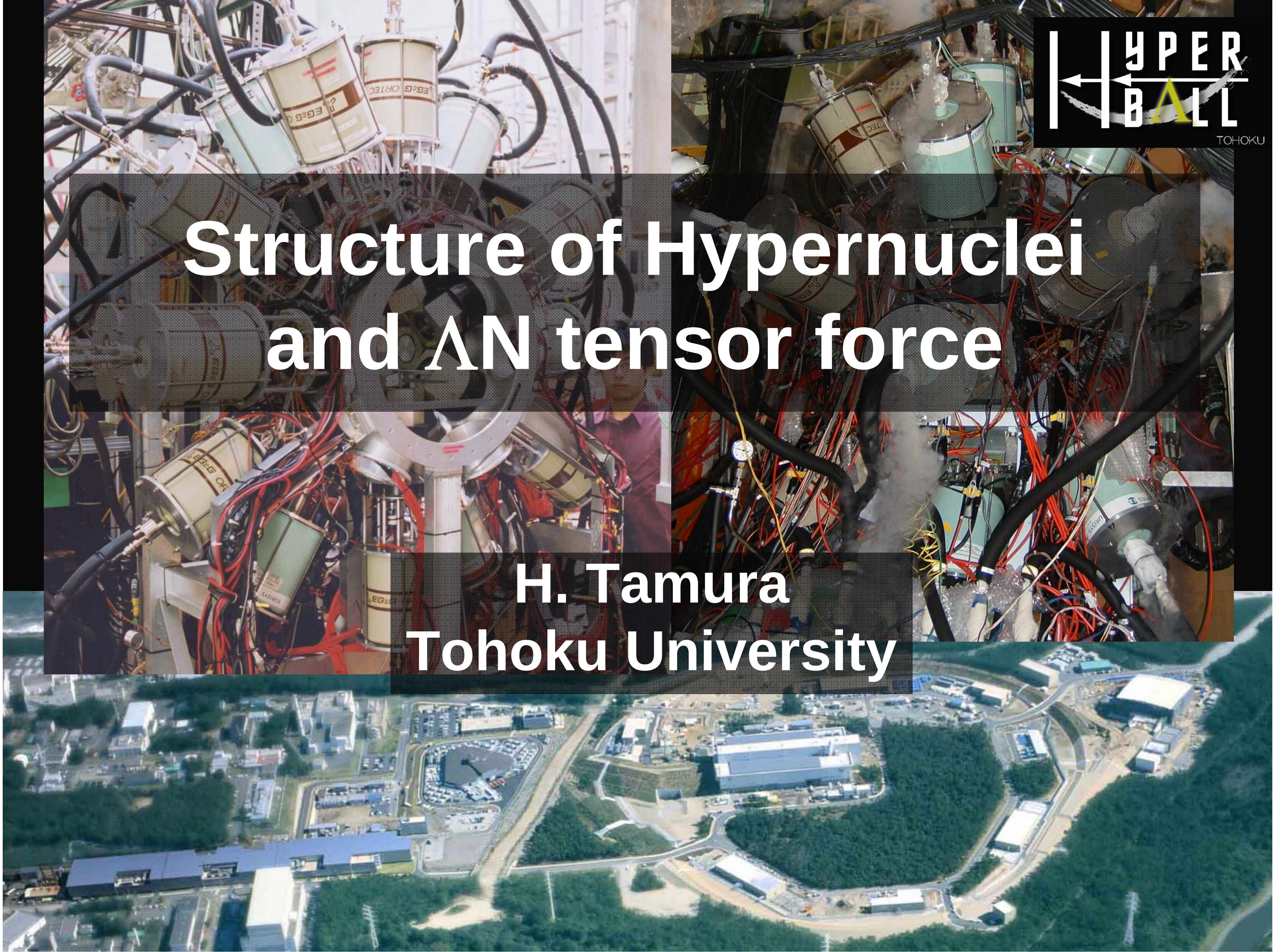
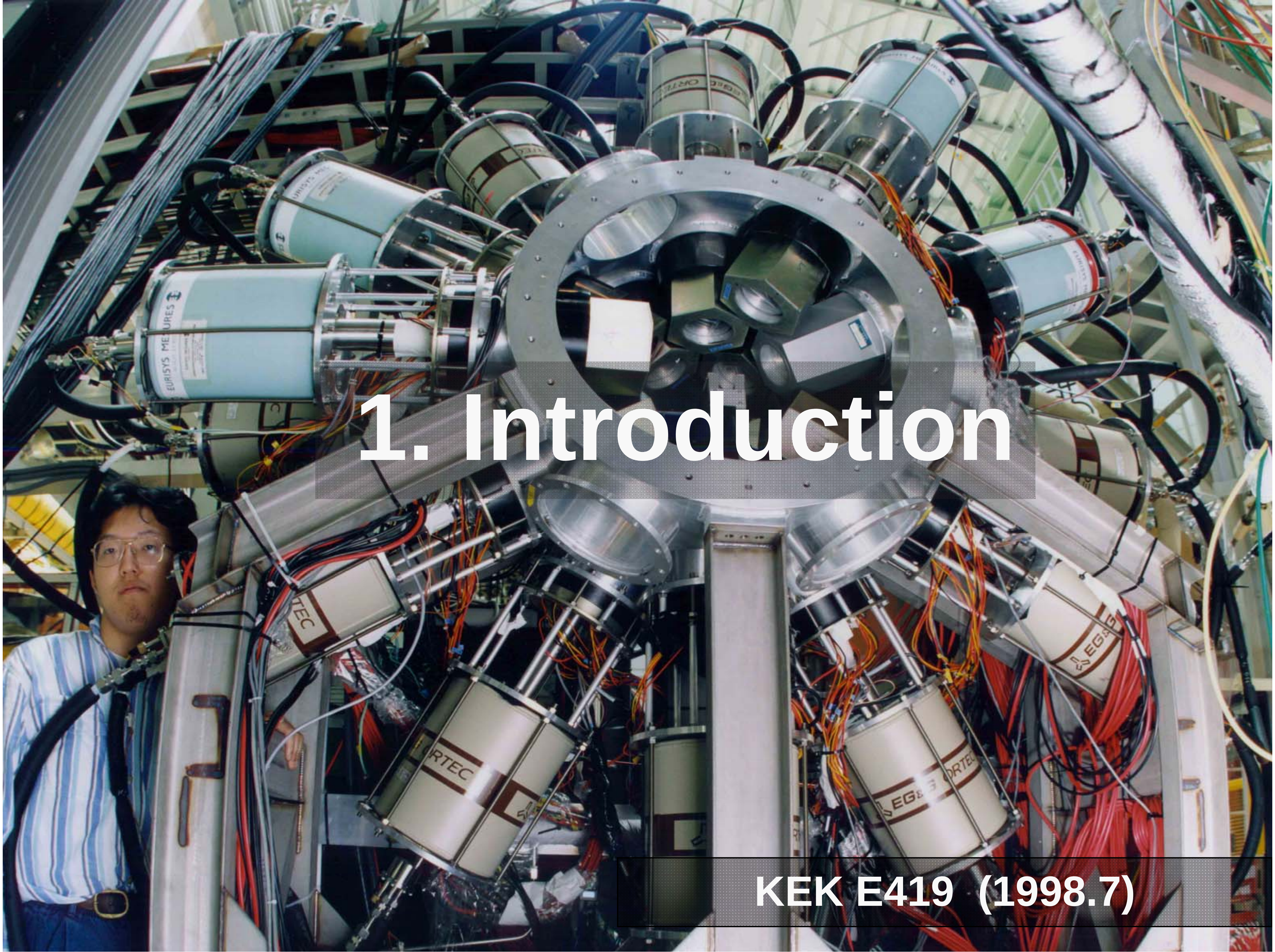


Structure of Hypernuclei and ΛN tensor force

H. Tamura
Tohoku University

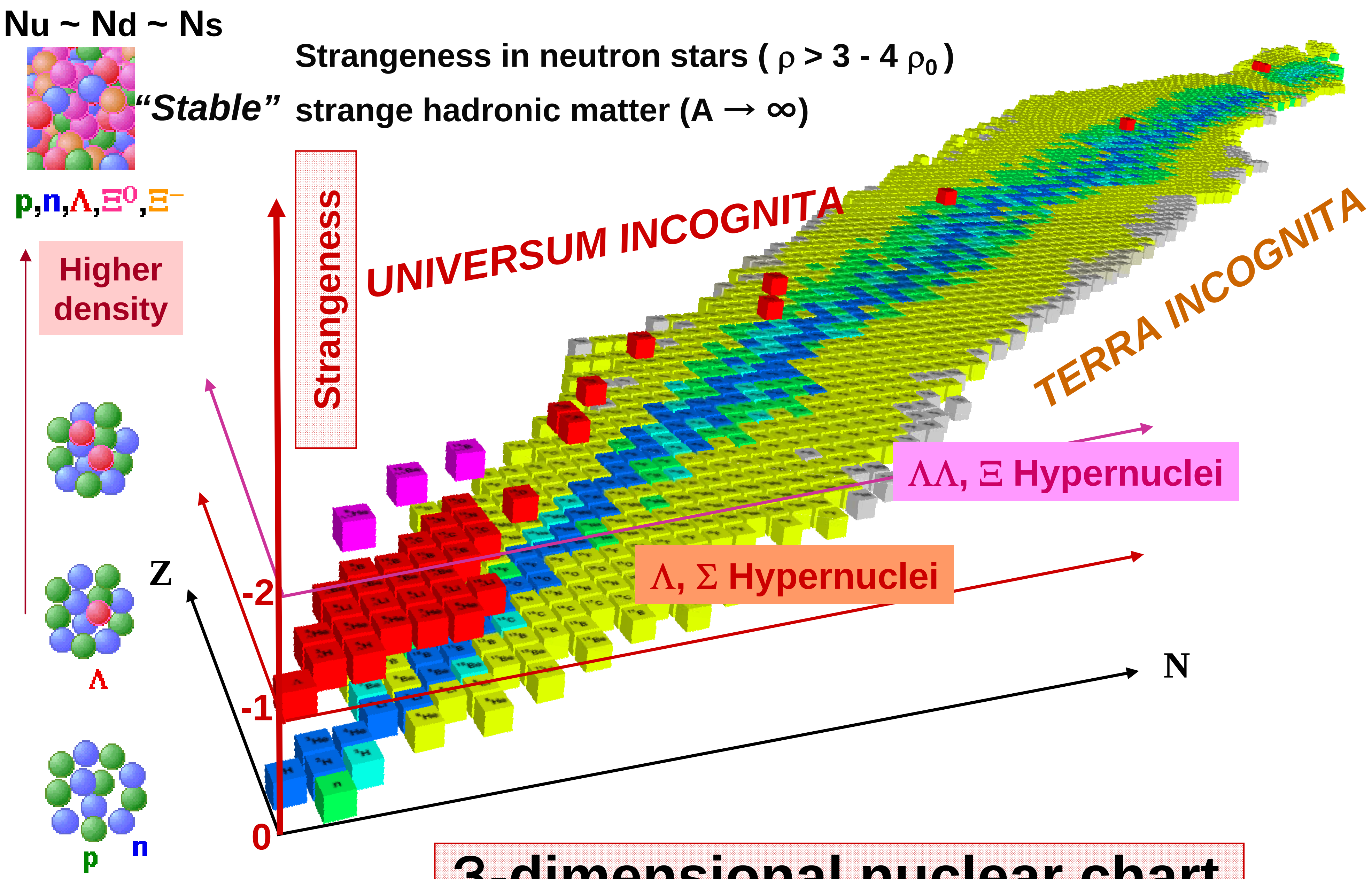
Contents

1. Introduction



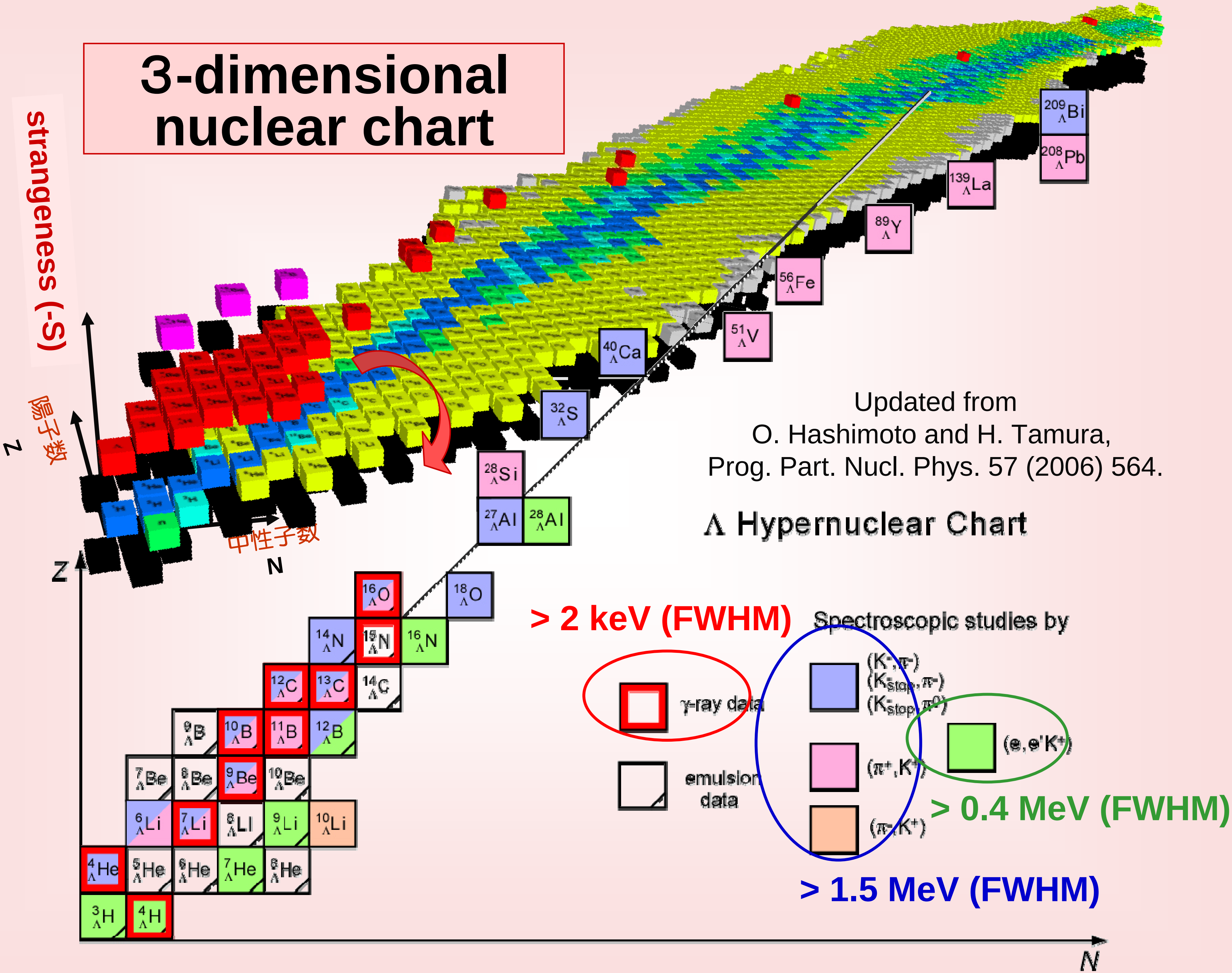
KEK E419 (1998.7)

World of matter made of u, d, s quarks



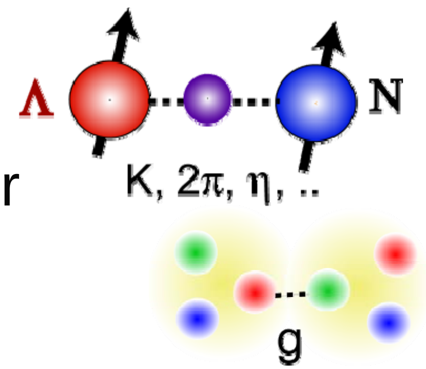
3-dimensional nuclear chart

by M. Kaneta inspired by HYP06 conference poster


3-dimensional nuclear chart
strangeness (-S)
陽子数
Z
中性子数
N
Updated from
O. Hashimoto and H. Tamura,
Prog. Part. Nucl. Phys. 57 (2006) 564.
Λ Hypernuclear Chart
> 2 keV (FWHM)
Spectroscopic studies by
γ-ray data
emulsion data
(K^-,π^-)
(K^-_{stop},π^-)
(K^-_{stop},π^0)
(π^+,K^+)
(π^-,K^+)
$(e,e'K^+)$
> 0.4 MeV (FWHM)
> 1.5 MeV (FWHM)
$^{209}_{\Lambda}Bi$
$^{208}_{\Lambda}Pb$
$^{139}_{\Lambda}La$
$^{89}_{\Lambda}Y$
$^{56}_{\Lambda}Fe$
$^{51}_{\Lambda}V$
$^{40}_{\Lambda}Ca$
$^{32}_{\Lambda}S$
$^{28}_{\Lambda}Si$
$^{27}_{\Lambda}Al$
$^{28}_{\Lambda}Al$
$^{16}_{\Lambda}O$
$^{18}_{\Lambda}O$
$^{14}_{\Lambda}N$
$^{15}_{\Lambda}N$
$^{16}_{\Lambda}N$
$^{12}_{\Lambda}C$
$^{13}_{\Lambda}C$
$^{14}_{\Lambda}C$
$^{9}_{\Lambda}B$
$^{10}_{\Lambda}B$
$^{11}_{\Lambda}B$
$^{12}_{\Lambda}B$
$^{7}_{\Lambda}Be$
$^{8}_{\Lambda}Be$
$^{9}_{\Lambda}Be$
$^{10}_{\Lambda}Be$
$^{6}_{\Lambda}Li$
$^{7}_{\Lambda}Li$
$^{8}_{\Lambda}Li$
$^{9}_{\Lambda}Li$
$^{10}_{\Lambda}Li$
$^{4}_{\Lambda}He$
$^{5}_{\Lambda}He$
$^{6}_{\Lambda}He$
$^{7}_{\Lambda}He$
$^{8}_{\Lambda}He$
$^{3}_{\Lambda}H$
$^{4}_{\Lambda}H$
Z
N

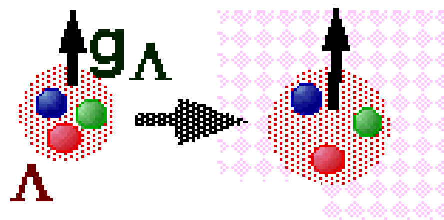
Motivation of Hypernuclear γ Spectroscopy

- **Baryon-Baryon interactions**
  - ΛN spin-dependent (spin-spin, spin-orbit, tensor) interactions, ΛN-ΣN interaction
  - Understand short-range nuclear forces in terms of quarks
  - Necessary to understand high density nuclear matter and strangeness mixing in neutron stars



- **Impurity effects** in nuclear structure
  - Changes of size/shape, symmetry, cluster/shell structure, collective motion

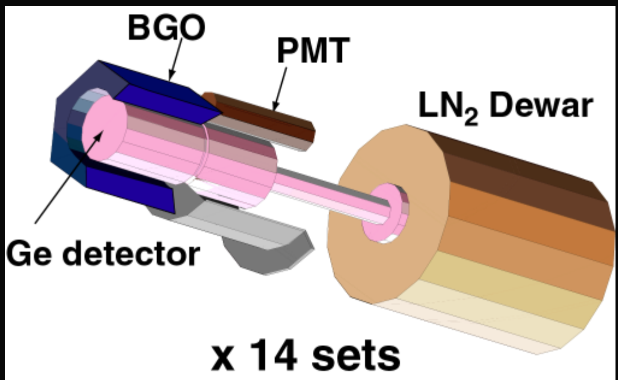
- **Nuclear medium effects** of baryons
  - Probed by hyperons free from Pauli effect

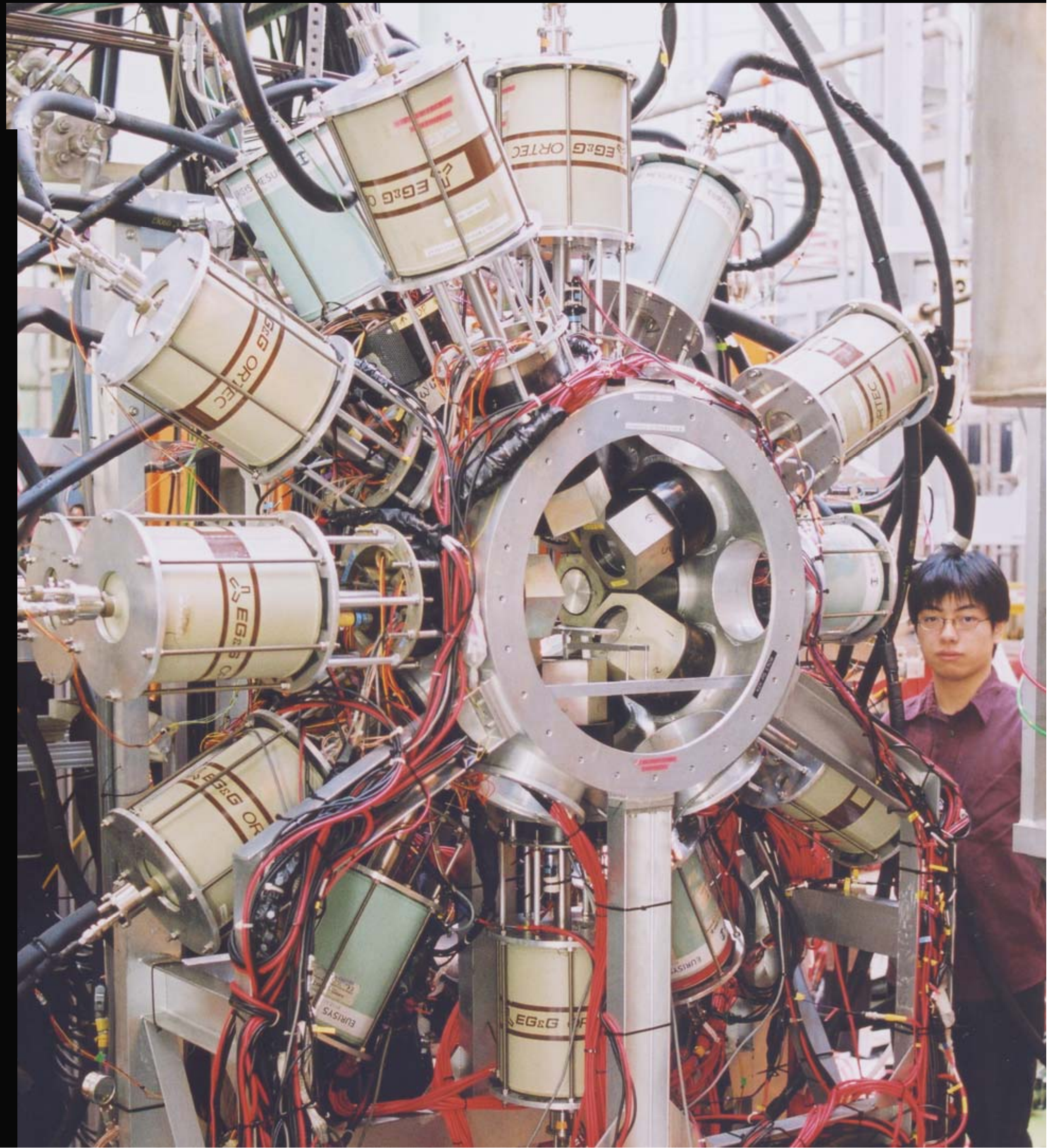


Ge detctor array: Hyperball

Constructed by Tohoku/ KEK/ Kyoto in 1998

- Large acceptance for small hypernuclear γ yields
  - Ge (r.e. 60%) x 14
    - Ω ~ 15%, ε ~ 3% at 1 MeV
- High-rate electronics for huge background
- BGO counters for π^0 and Compton suppression

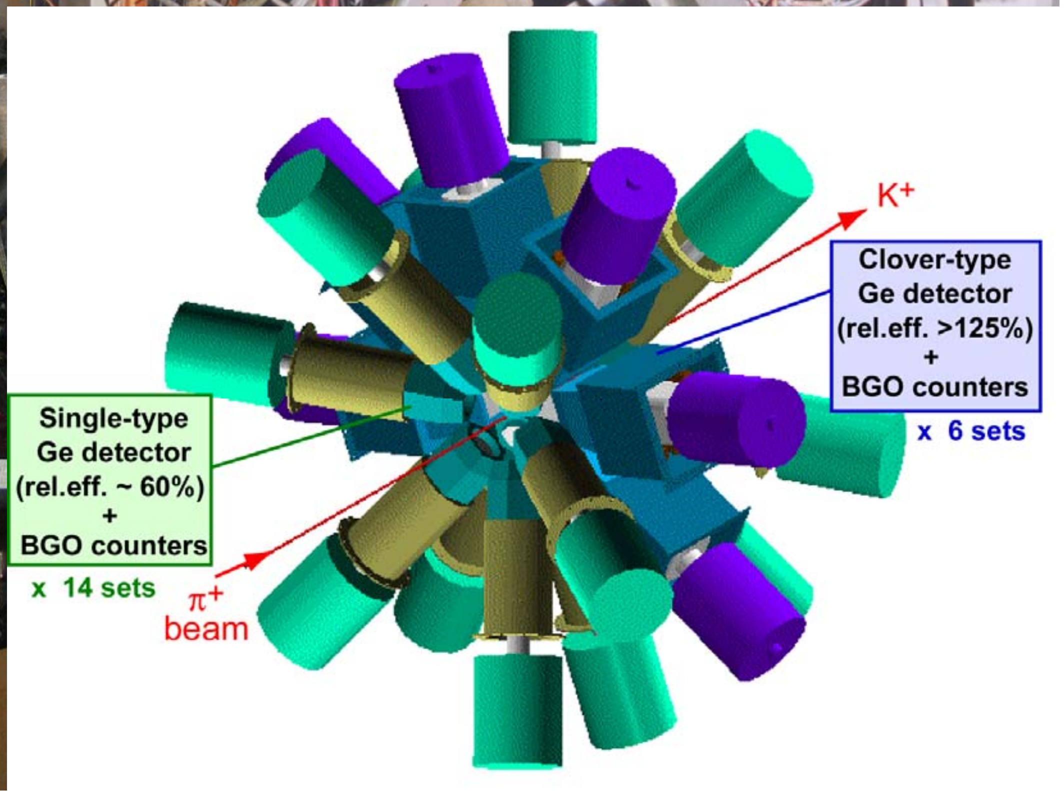




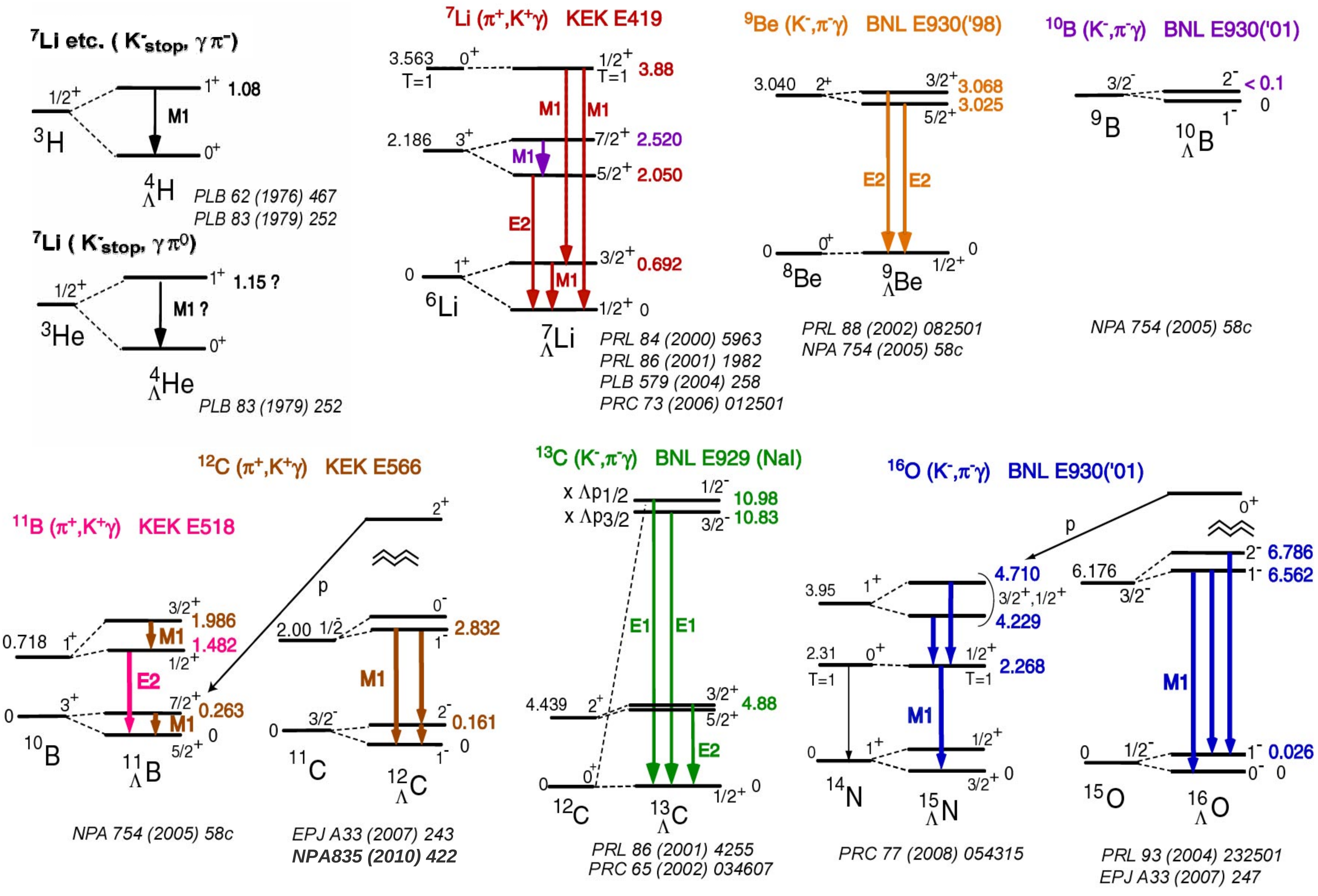
Ge detctor array: Hyperball

Upgraded to Hyperball2 in Tohoku (2005~)

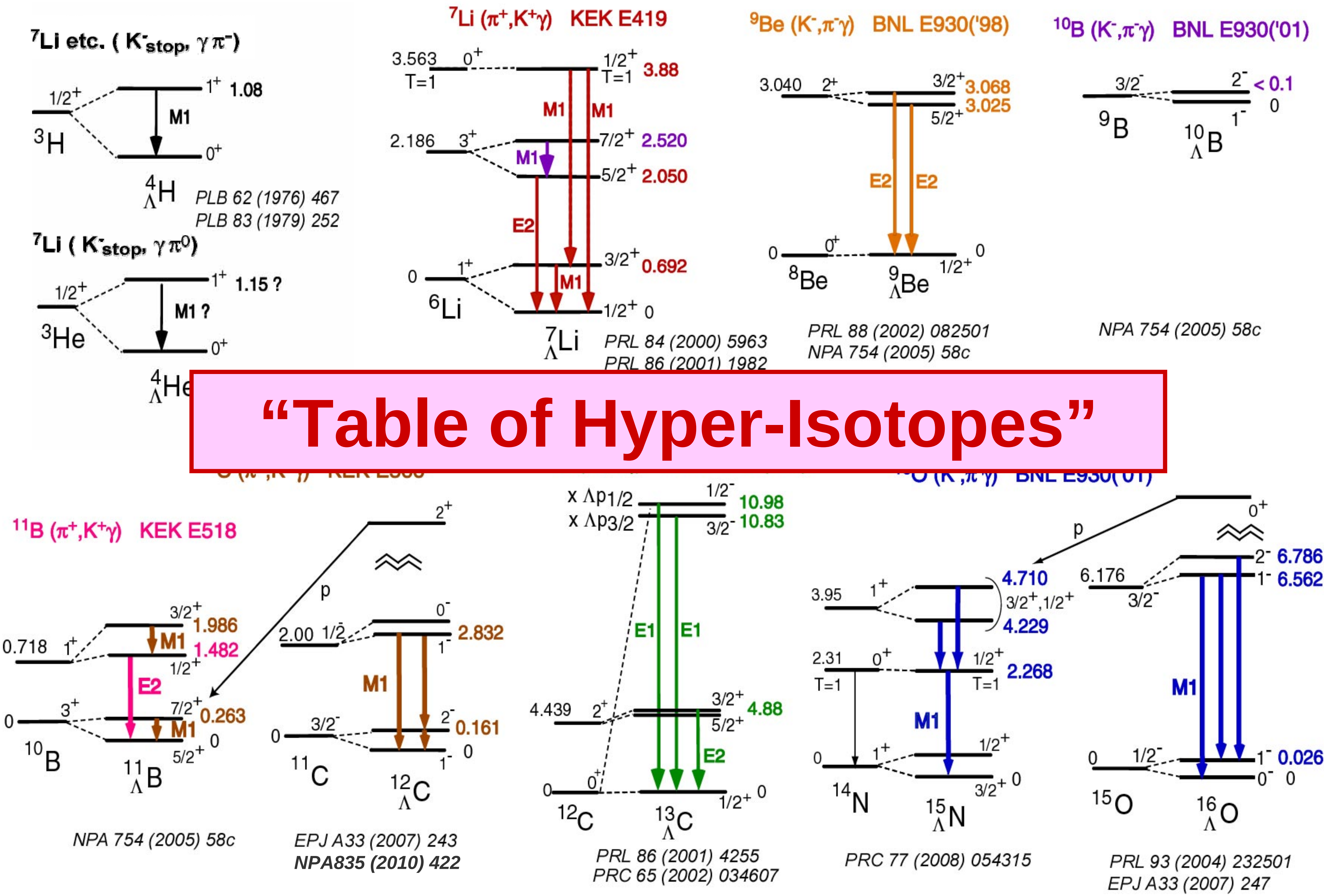
Efficiency 2.4% -> ~4%



Hypernuclear γ-ray data (2010)

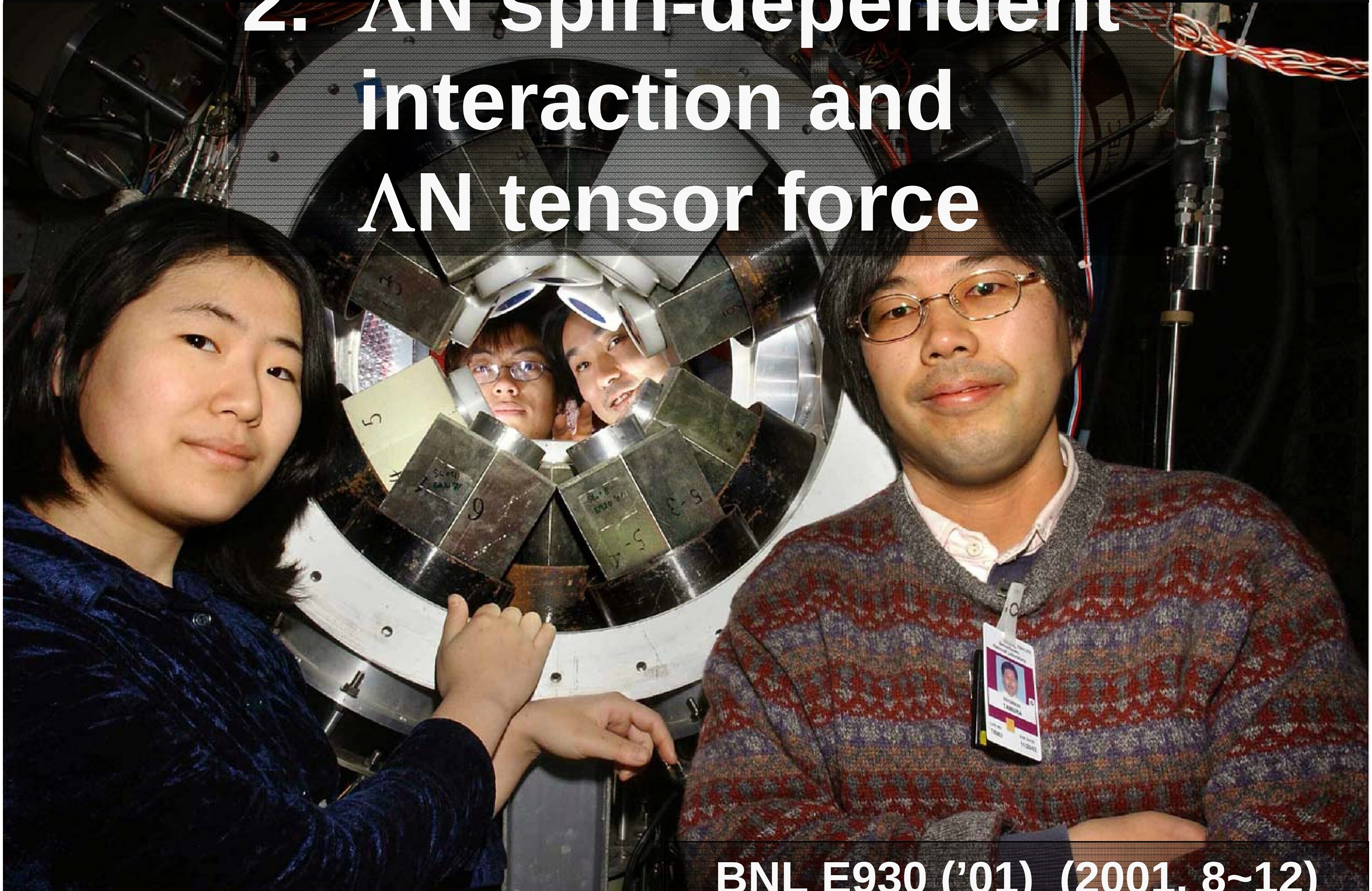


Hypernuclear γ-ray data (2010)



“Table of Hyper-Isotopes”

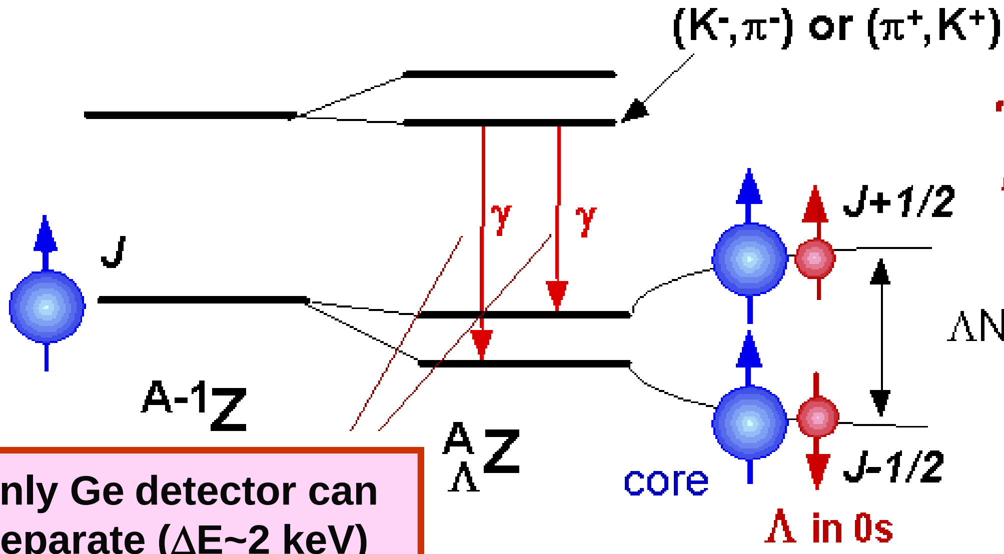
2. ΛN spin-dependent interaction and ΛN tensor force



BNL E930 ('01) (2001. 8~12)

ΛN spin-dependent interactions

- **Low-lying levels of Λ hypernuclei**



"Hypernuclear Fine Structure"

split by ΛN spin-dependent interactions $\lesssim$ 0.1 MeV

Only Ge detector can separate (ΔE~2 keV)

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

- **Two-body ΛN effective interaction**

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

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

$\bar{V}$ $\quad \Delta \quad S_\Lambda \quad S_N \quad T$

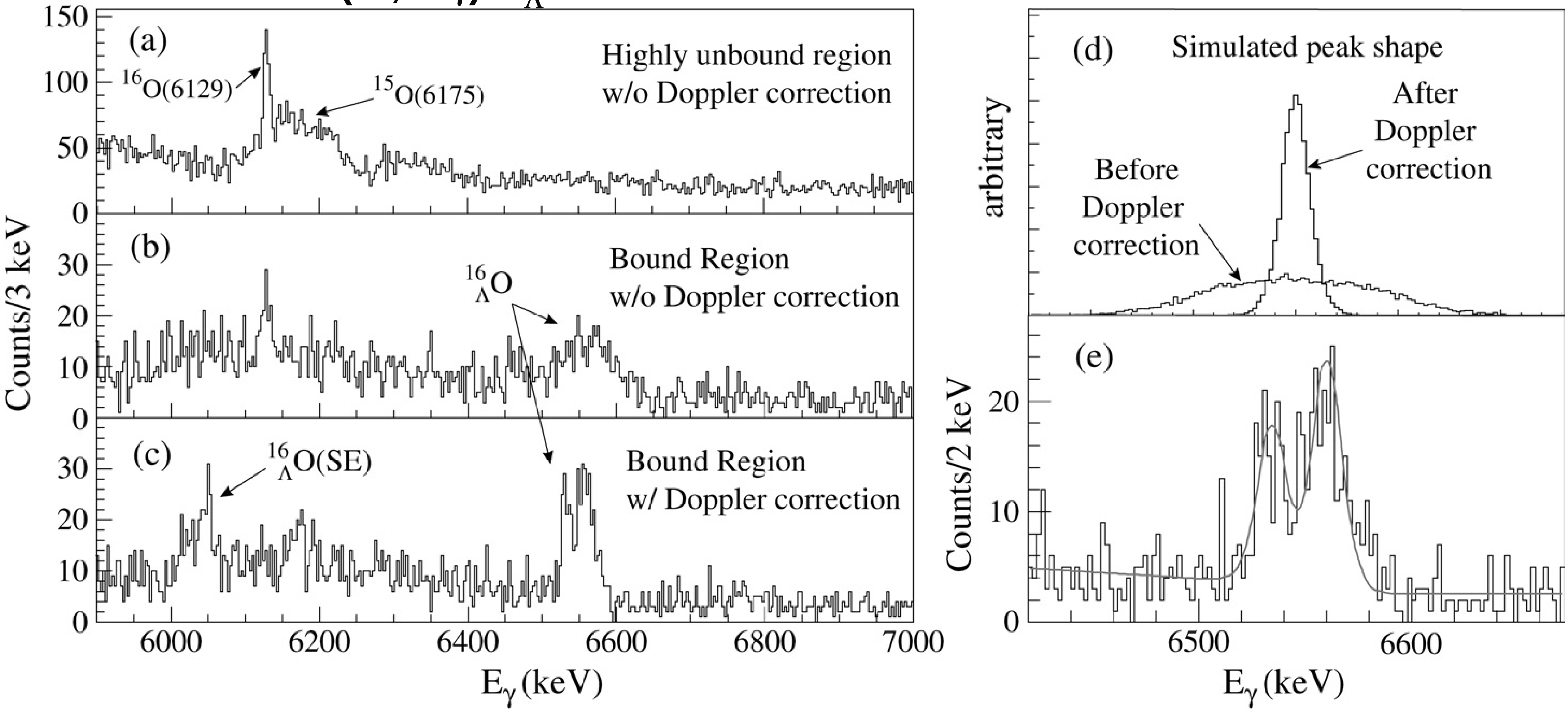
Well know from U_Λ = - 30 MeV

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

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

Example: $^{16}_{\Lambda}O$ γ-rays from ^{16}O (K^-, π^- γ) BNL E930

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

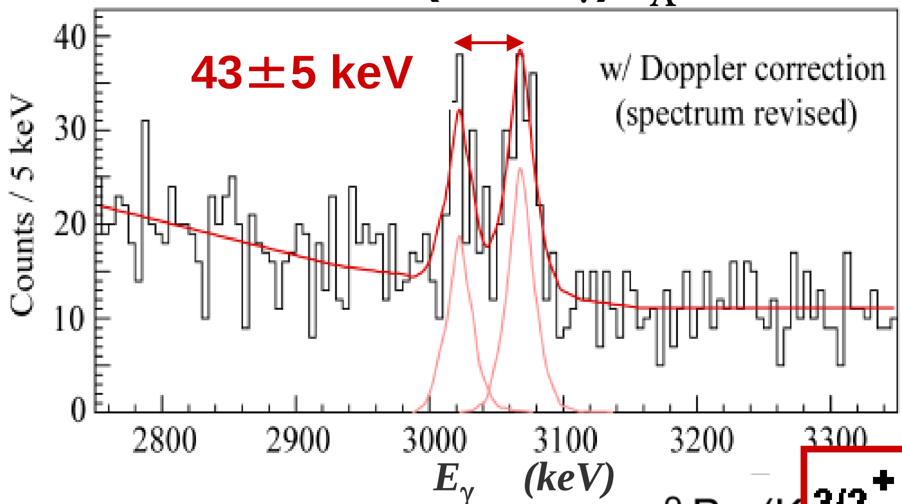


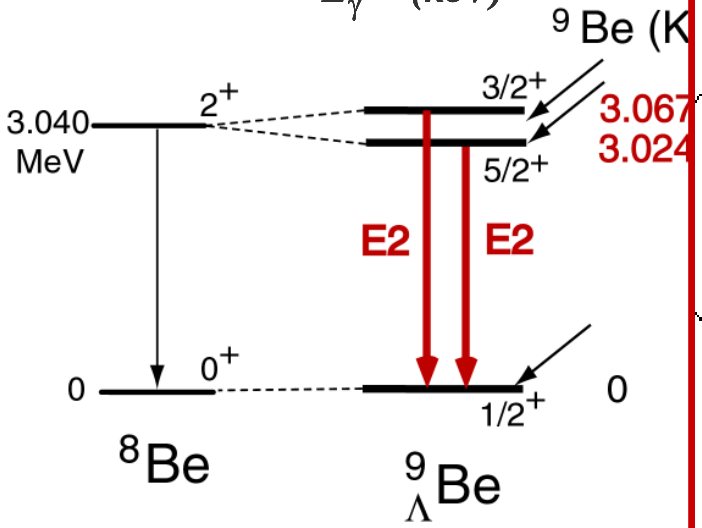
Ukai et al., PRL 93 (2004) 232501;
Ukai et al., PRC 77 (2008) 54315.

Observation of Hypernuclear Fine Structure

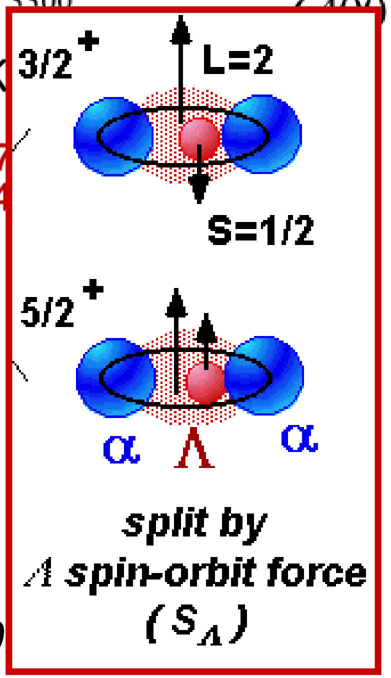
BNL E930 (AGS D6 line + Hyperball)

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

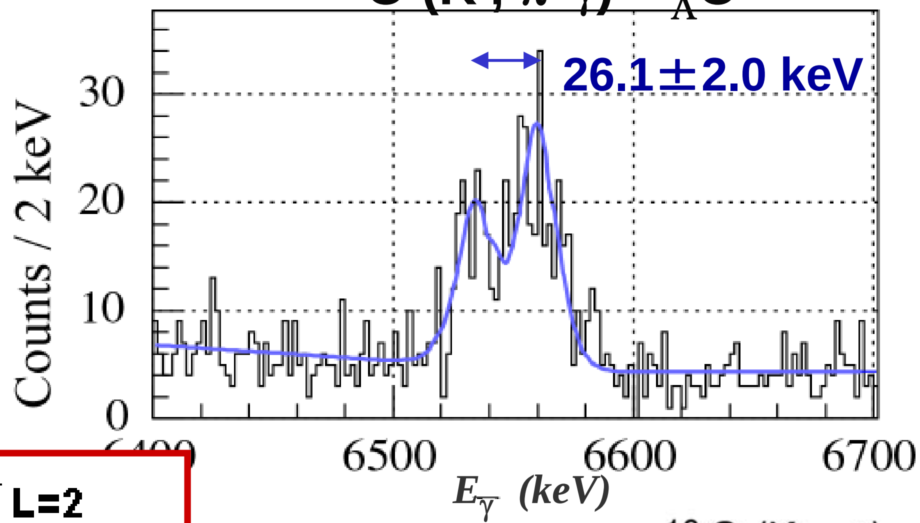


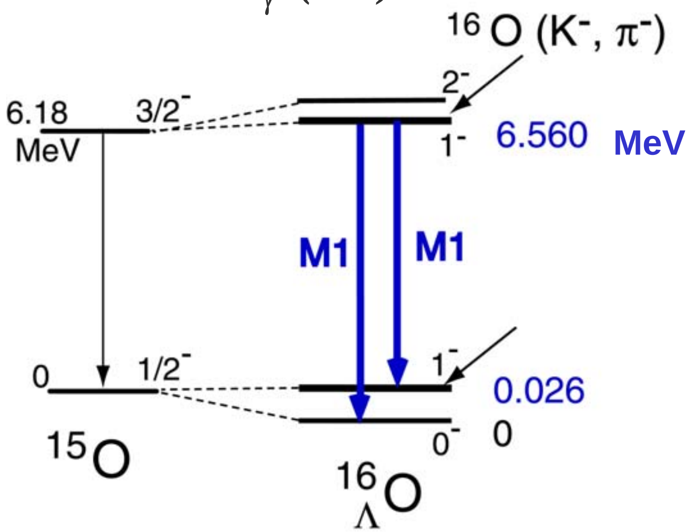


Akikawa et al., PRL 88 (2002) 08250



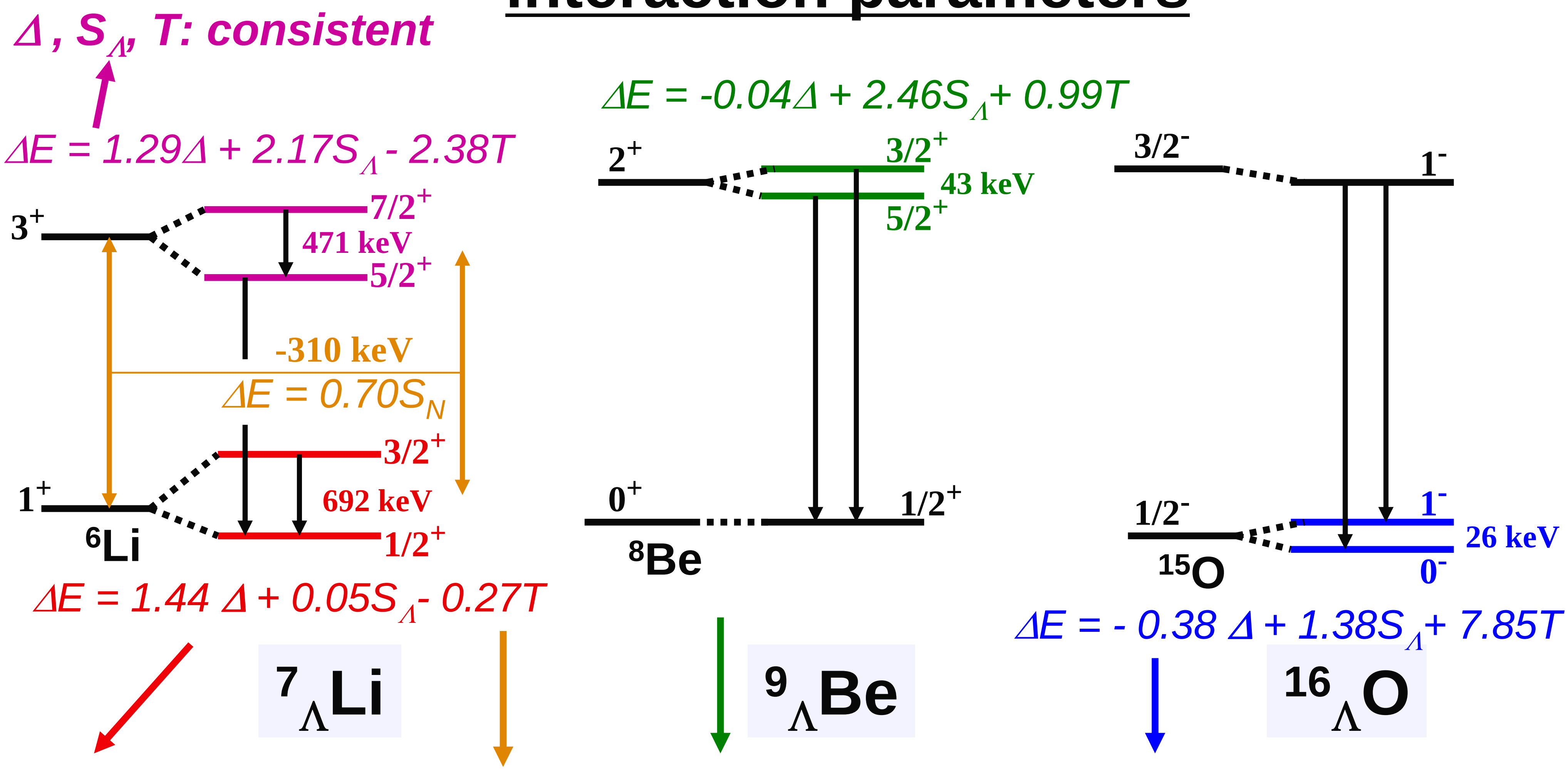
$^{16}O\ (K^{-}, \pi^{-}\ \gamma)\ ^{16}_{\Lambda}O$





Ukai et al., PRL 93 (2004) 232501

Determination of the spin-dependent interaction parameters



$\Delta = 0.43$ MeV $\quad S_N = -0.4$ MeV $\quad S_\Lambda = -0.01$ MeV $\quad T = 0.03$ MeV

PRL 86 ('00) 5963 PRL 88 ('02) 082501 PRL 93 (2004) 232501

All the spin-dependent force parameters determined.

This parameter set reproduces almost all the p-shell level data.

Features of ΛN interaction
“Nuclear force without pion”

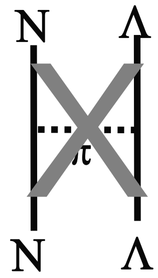
Experimentally

- Spin-averaged ΛN force strength weaker (~2/3) than NN
- All the Λ-spin-dependent forces are small.

  Spin-spin force 1/10 of NN

  Spin-orbit force 1/40 of NN

Probably because s quark spin is ineffective than u,d



Theoretically

- Λ has no isospin (ud quarks couple to S=0,T=0)

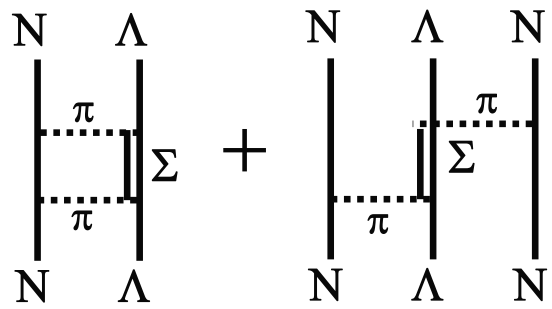
-> one π/ρ exchange forbidden. Main sources are K, σ, ω exch.

  Shorter range than NN

  Weaker tensor force than NN

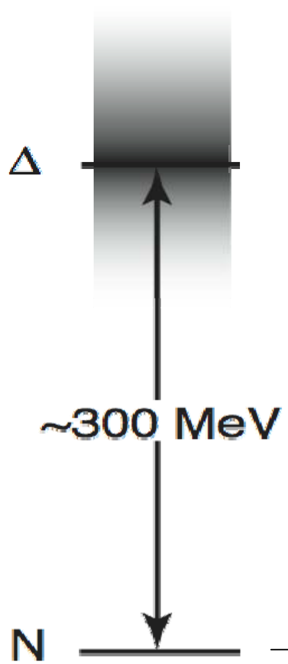
- Σ–Λ coupling force (2π exchange) from ΣN–ΛN tensor force gives large effects : $m_\Sigma - m_\Lambda < m_\Delta - m_N$

  –> ΛNN 3 body force is more important than NNN



Can we use a Λ to investigate the effect of the tensor force to the nuclear structure?

Baryon mixing and three-body force in hypernuclei

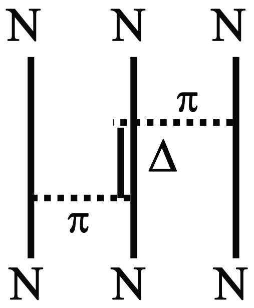


Mixing ∝ 1/ΔE
-> Large Σ mixing (~a few % ?)

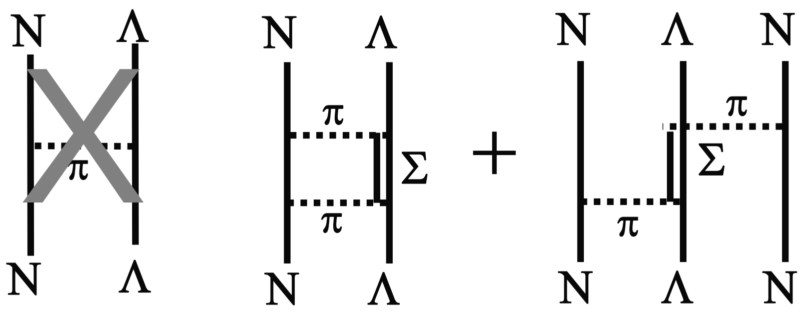
πN→ πN, Δ → πN : experimentally known

πΛ → πΛ, Σ → πΛ : not known – theoretical ($SU(3)_f$) input necessary

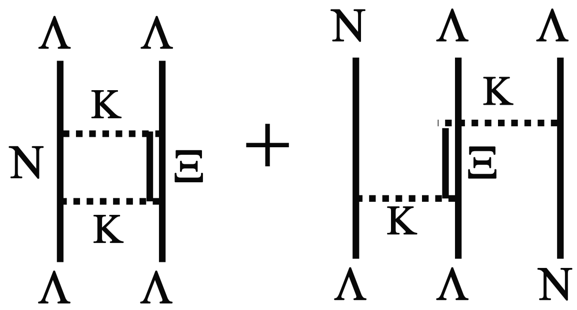
S = 0



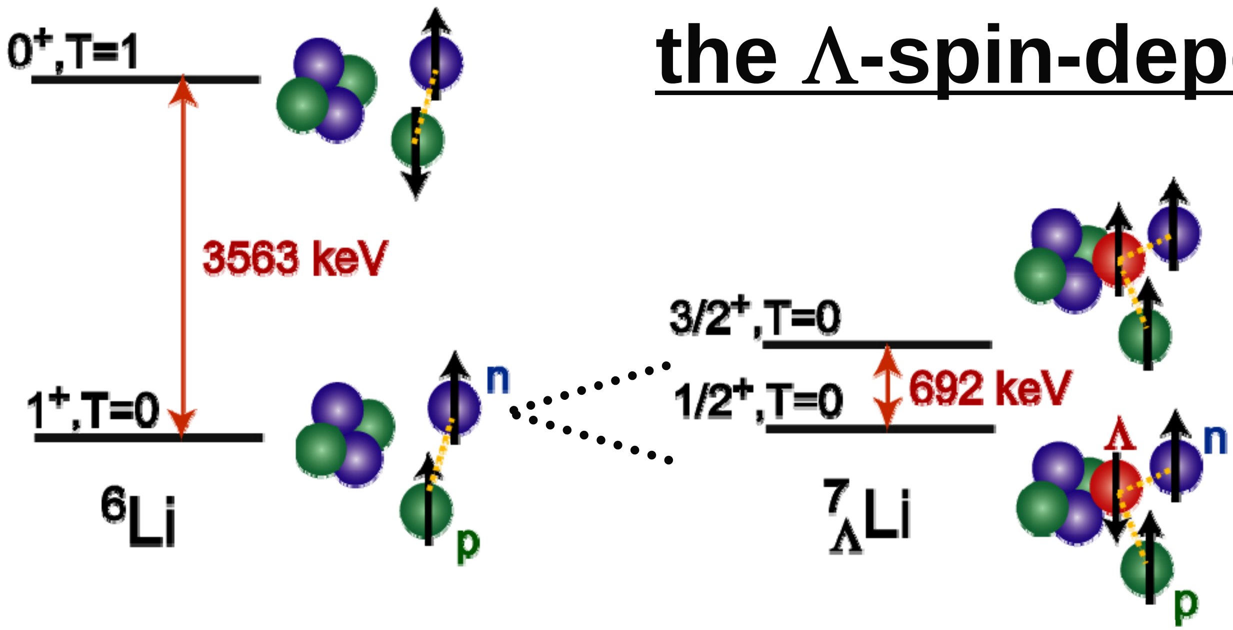
S = -1



S = -2



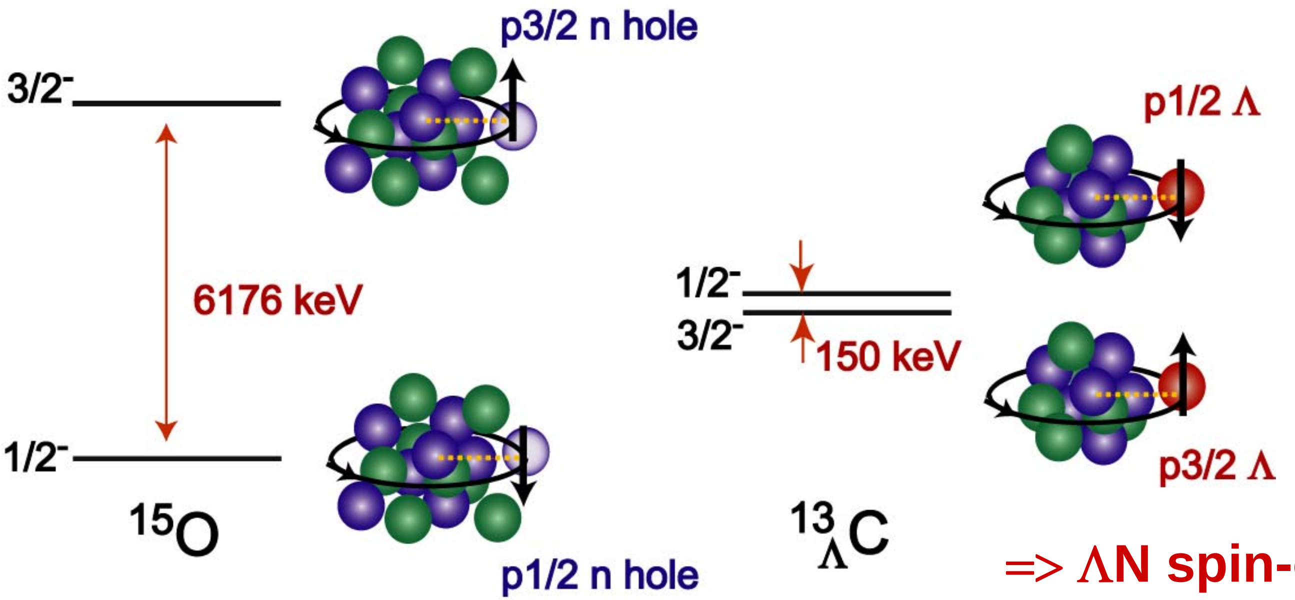
How weak are the Λ-spin-dependent forces?



Tamura et al., PRL 84 (2000) 5963

$\Delta = 0.42$ MeV

=> ΛN spin-spin force
~ 1/10 of NN spin-isospin force



Ajimura et al., PRL 86 (2001) 4255

($S_\Lambda = -0.01$ MeV)

=> ΛN spin-orbit force
~ 1/40 of NN spin-orbit force

Effective ΛN tensor force for p-shell hypernuclei in the shell model

- Large contribution in doublet spacings of $p_{1/2}$ shell hypernuclei

  j j coupling : $\Delta E = -1/3\Delta + 4/3\, S_\Lambda + 8\, T$,

  Shell model calc ${}^{16}_{\Lambda}O$: $\Delta E = -0.38\,\Delta + 1.38 S_\Lambda + 7.85 T$

  T is determined only by ${}^{16}_{\Lambda}O_{gs}(1^-,0^-)$ *spacing but consistent for other level energies.*

- Some contribution of ΛN tensor force to the Λ's LS splitting exists.

  Shell model calc ${}^{9}_{\Lambda}Be$: $\Delta E = -0.04\Delta + 2.46 S_\Lambda + 0.99 T$

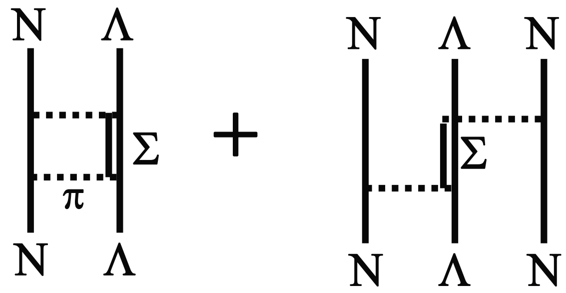
Millener's approach for ΛN-ΣN coupling force

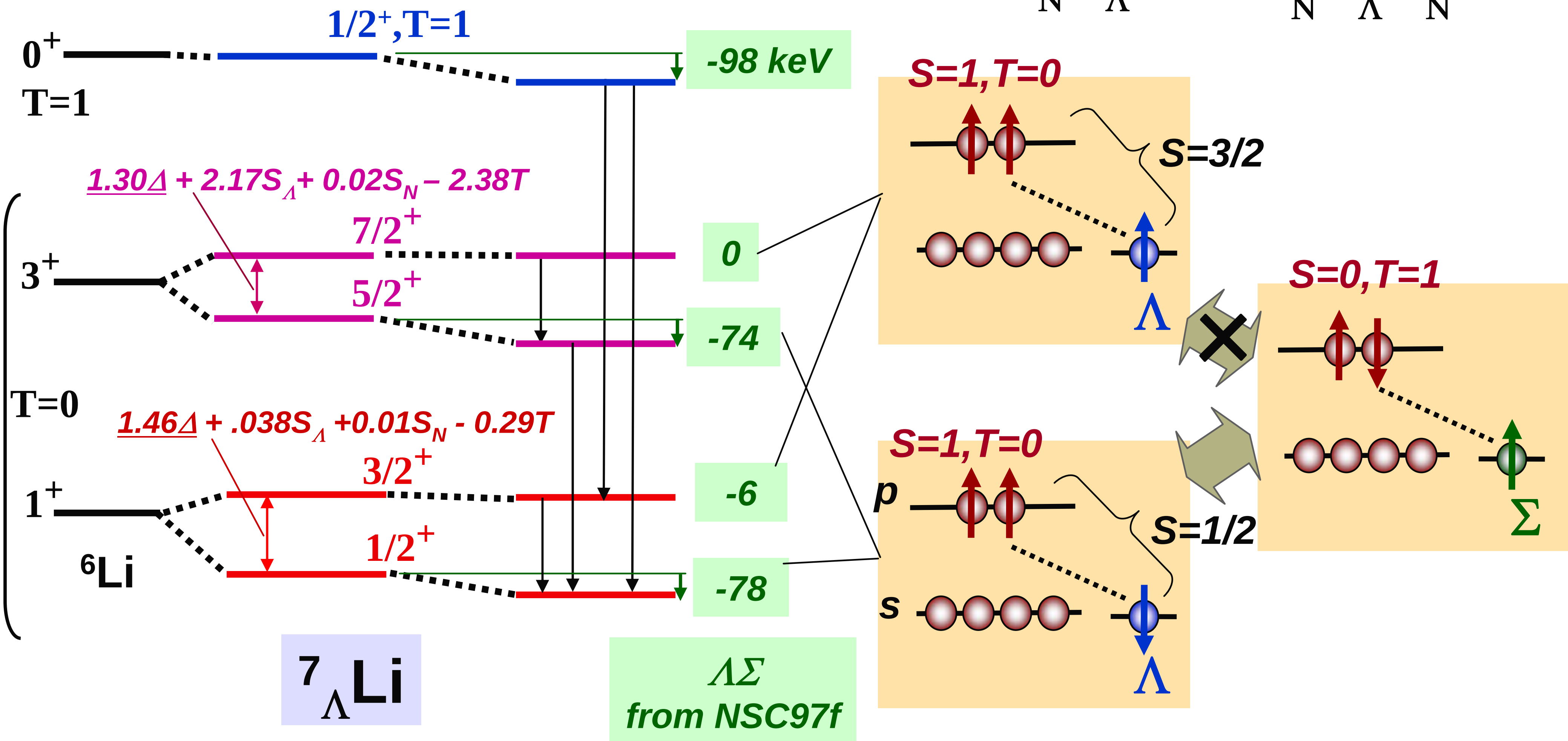
Millener, Lecture Notes in Physics 724, Springer (2007) p.31

$u = \langle p_N^{A-5} s_\Sigma (J) \,|\, V \,|\, p_N^{A-5} s_\Lambda (J) \rangle$ *V: NSC97f through G-matrix (spin-dependent)*

Energy shift $(\Lambda\Sigma) = u^2 / (m_\Sigma - m_\Lambda)$

($s_N^4 s_\Sigma$ - $s_N^4 s_\Lambda$ coupling has no spin-dependence and can be incorporated in effective 2B ΛN central force.)





Millener's parameter set

A=7~9: $\Delta = 0.430 \quad S_\Lambda = -0.015 \quad S_N = -0.390 \quad T = 0.030$ MeV

A=10~16: $\Delta = 0.330 \quad S_\Lambda = -0.015 \quad S_N = -0.350 \quad T = 0.0239$ MeV

Calculated from G-matrix using ΛN–ΣN force in NSC97f

doublet spacing

	J_u^π	J_l^π	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
			contribution of each term (keV)					keV	
$^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
$^{7}_{\Lambda}$Li	$7/2^+$	$5/2^+$	74	557	−32	−8	−71	494	471
$^{8}_{\Lambda}$Li	2^-	1^-	151	396	−14	−16	−24	450	(442)
$^{9}_{\Lambda}$Li	$5/2^+$	$3/2^+$	116	530	−17	−18	−1	589	
$^{9}_{\Lambda}$Li	$3/2_2^+$	$1/2^+$	−80	231	−13	−13	−93	−9	
$^{9}_{\Lambda}$Be	$3/2^+$	$5/2^+$	−8	−14	37	0	28	44	43
$^{10}_{\Lambda}$B	2^-	1^-	−15	188	−21	−3	−26	120	< 100
$^{11}_{\Lambda}$B	$7/2^+$	$5/2^+$	56	339	−37	−10	−80	267	264
$^{11}_{\Lambda}$B	$3/2^+$	$1/2^+$	61	424	−3	−44	−10	475	505
$^{12}_{\Lambda}$C	2^-	1^-	61	175	−12	−13	−42	153	161
$^{15}_{\Lambda}$N	$1/2_1^+$	$3/2_1^+$	44	244	34	−8	−214	99	
$^{15}_{\Lambda}$N	$3/2_2^+$	$1/2_2^+$	65	451	−2	−16	−10	507	481
$^{16}_{\Lambda}$O	1^-	0^-	−33	−123	−20	1	188	23	26
$^{16}_{\Lambda}$O	2^-	1_2^-	92	207	−21	1	−41	248	224

D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

Millener's parameter set

A=7~9 … MeV

Agreement looks almost perfect with the ΣΛ coupling effect !
-> NSC97f seems good for ΣΛ coupling (but we need more data).

Calculated from G-matrix using ΛN–ΣN force in NSC97f

doublet spacing

	J^π_u	J^π_l	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
			contribution of each term (keV)					keV	
${}^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
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${}^{16}_{\Lambda}$O	1^-	0^-	−33	−123	−20	1	188	23	26
${}^{16}_{\Lambda}$O	2^-	1^-_2	92	207	−21	1	−41	248	224

D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

Feedback to YN interaction models

Nijmegen meson-exchange models

Via G-matrix calc.

	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	0.421	-0.149	-0.238	0.055
ESC04a	0.381	-0.108	-0.236	0.013
ESC08a	0.146	-0.074	-0.241	0.055
("Quark"		0.0	-0.4	)
Exp.	0.4	-0.01	-0.4	0.03

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

spin-spin:

Δ = 0.33--0.43 MeV **=> *NSC97f selected*** **(consistent with $^4_\Lambda$H(1$^+$,0$^+$))**

spin-orbit:

S_Λ = -0.01 MeV (SLS+ALS)

S_N = -0.4 MeV (SLS-ALS)

=> ***All Nijmegen models fail.***
Quark model looks OK.

$^9_\Lambda$Be = $\alpha\alpha\Lambda$ model

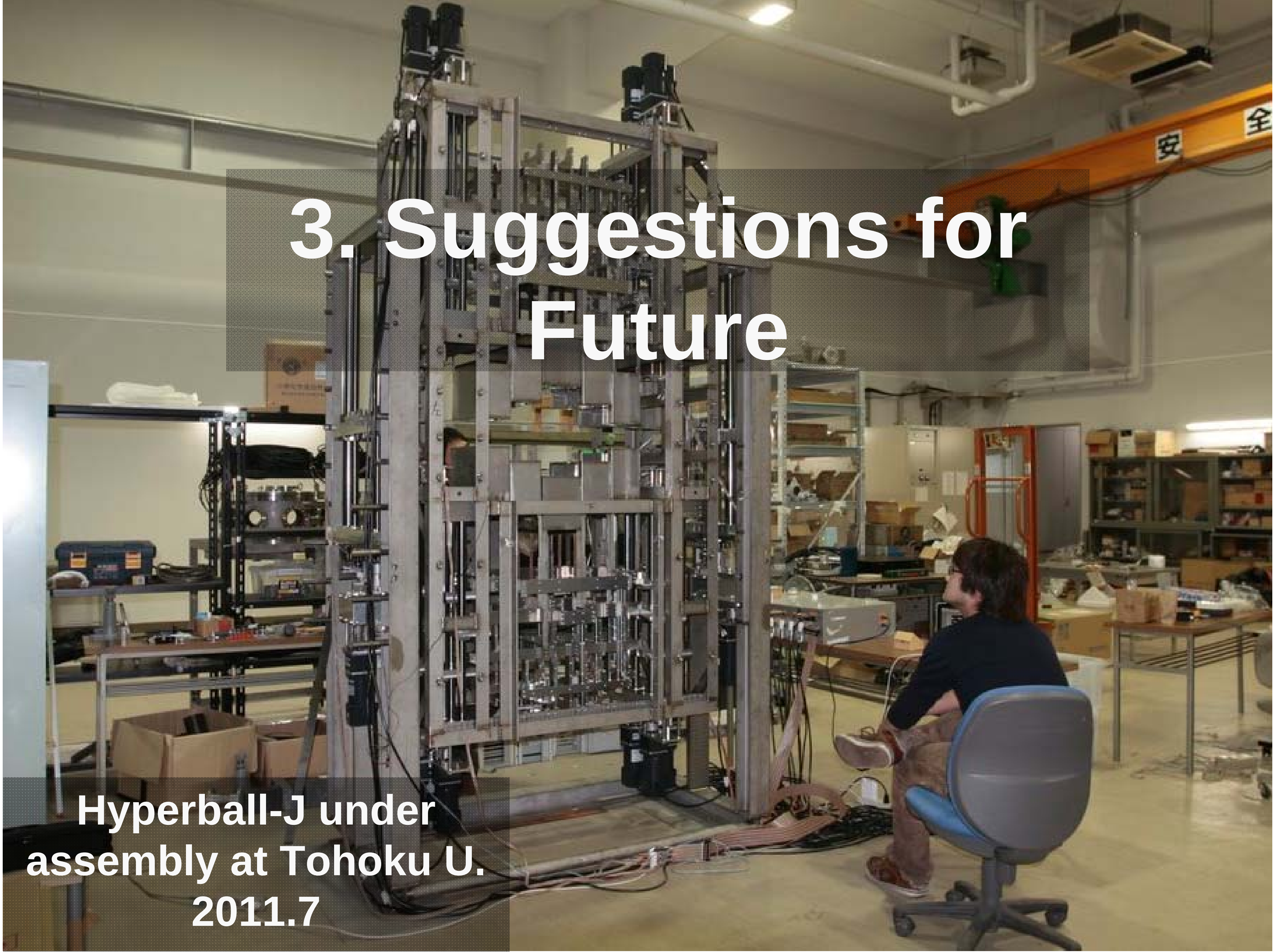
Hiyama et al., PRL 85 (2000) 270

Fujiwara et al. Prog.Part.Nucl.Phys.58 (2007) 439.

tensor:

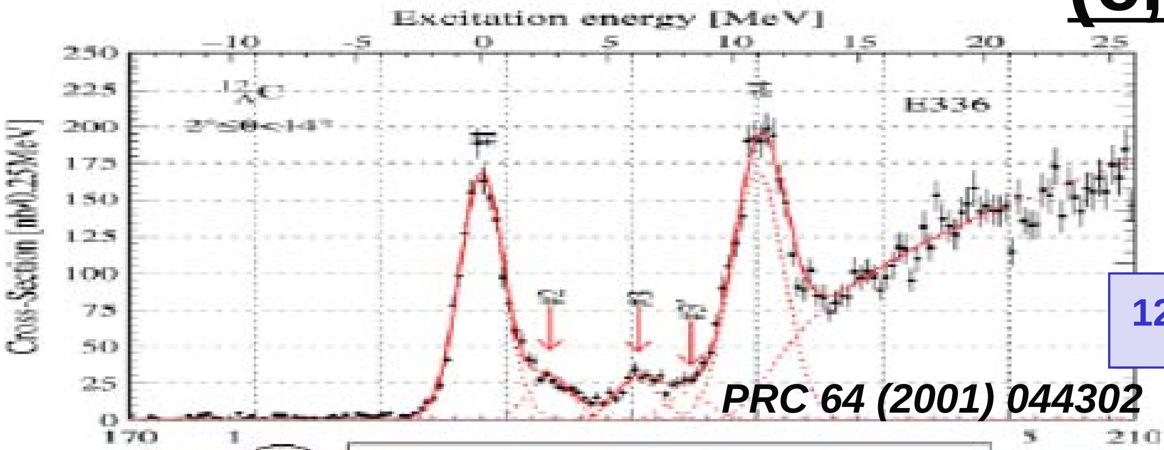
T = 0.03 MeV **=> *Nijmegen models OK***

3. Suggestions for Future



Hyperball-J under assembly at Tohoku U. 2011.7

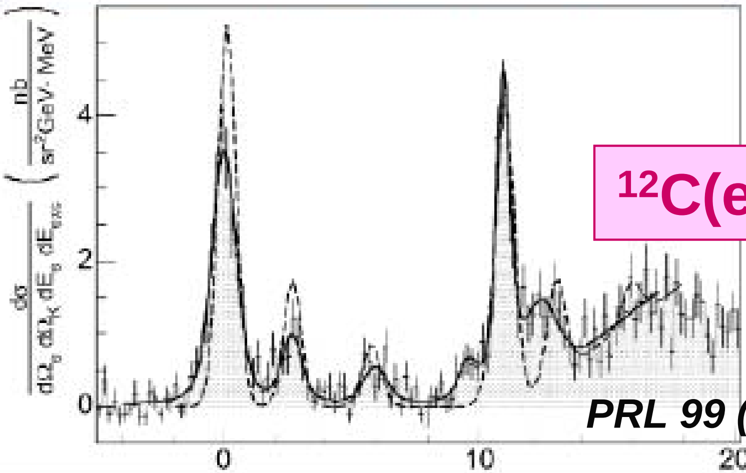
(e,eK$^+$) reaction at JLab -- Improvement of Resolution



PRC 64 (2001) 044302

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

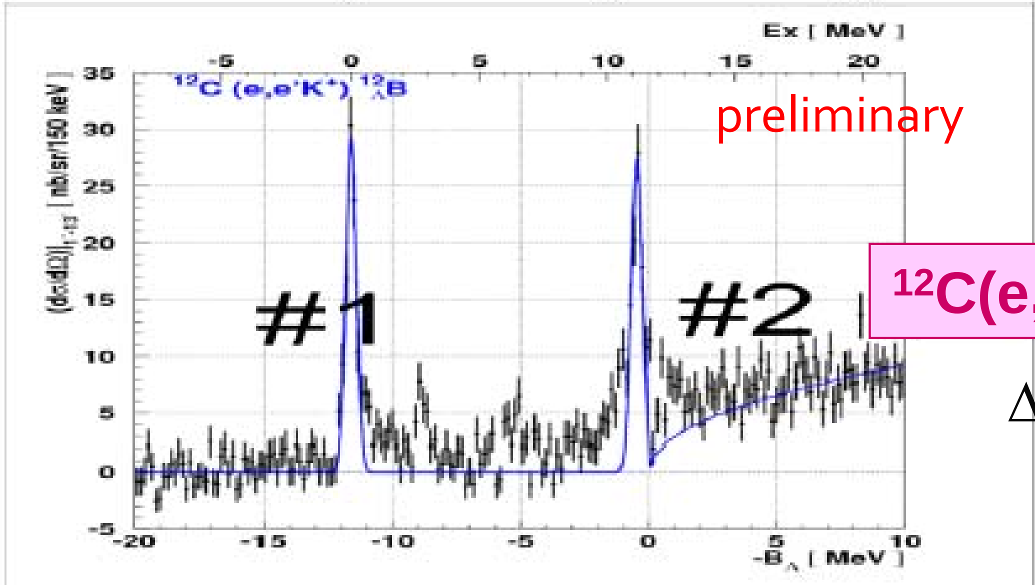
ΔE = 2 MeV (FWHM)



PRL 99 (2007) 052501

$^{12}C(e,e'K^+)^{12}{}_\Lambda B$ @ JLab Hall A

ΔE ~ 0.65 MeV (FWHM)

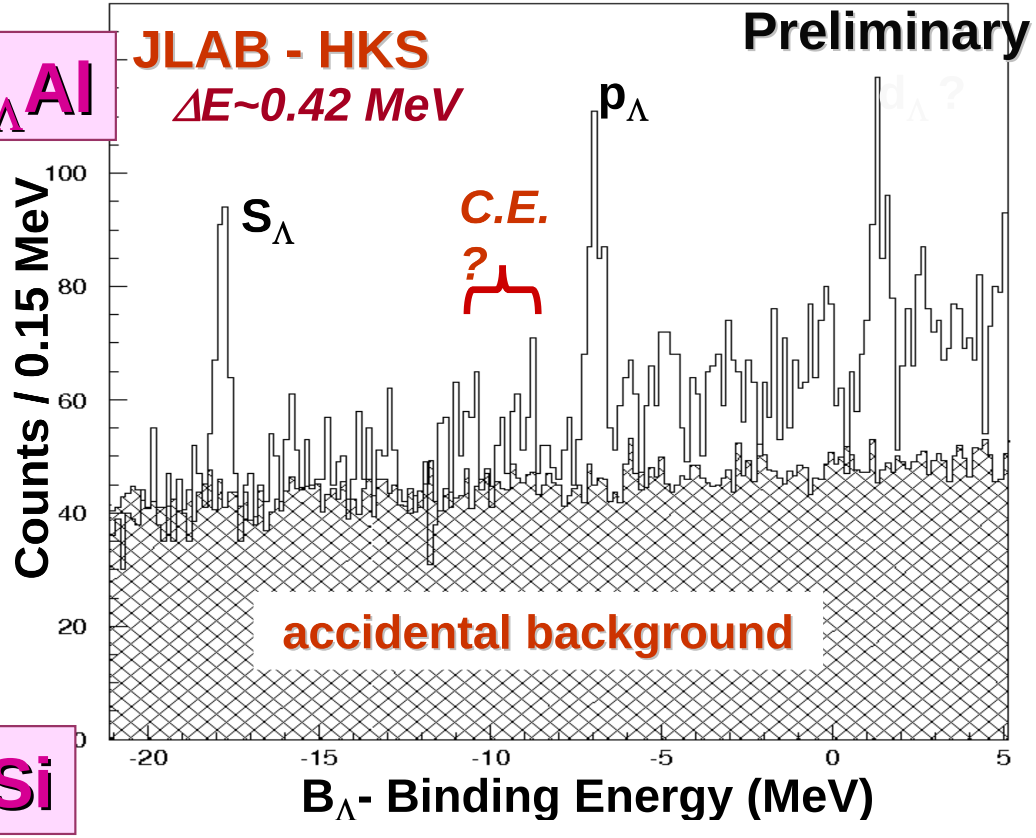


$^{12}C(e,e'K^+)^{12}{}_\Lambda B$ @ JLab Hall C

ΔE ~ 0.5 MeV (FWHM)

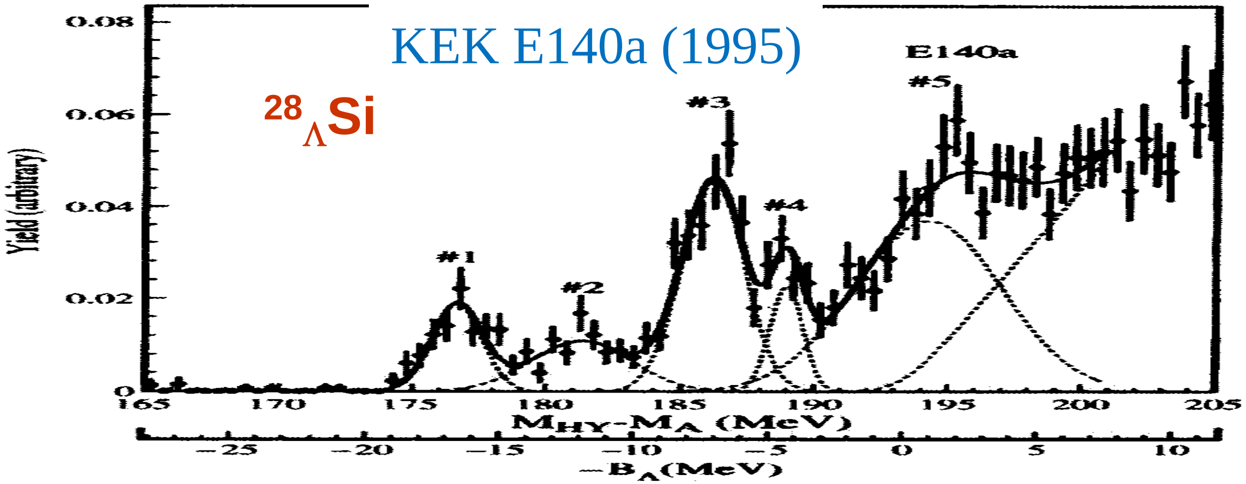
$^{28}_{\Lambda}$Al – spectroscopy by (e,e'K$^+$)

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



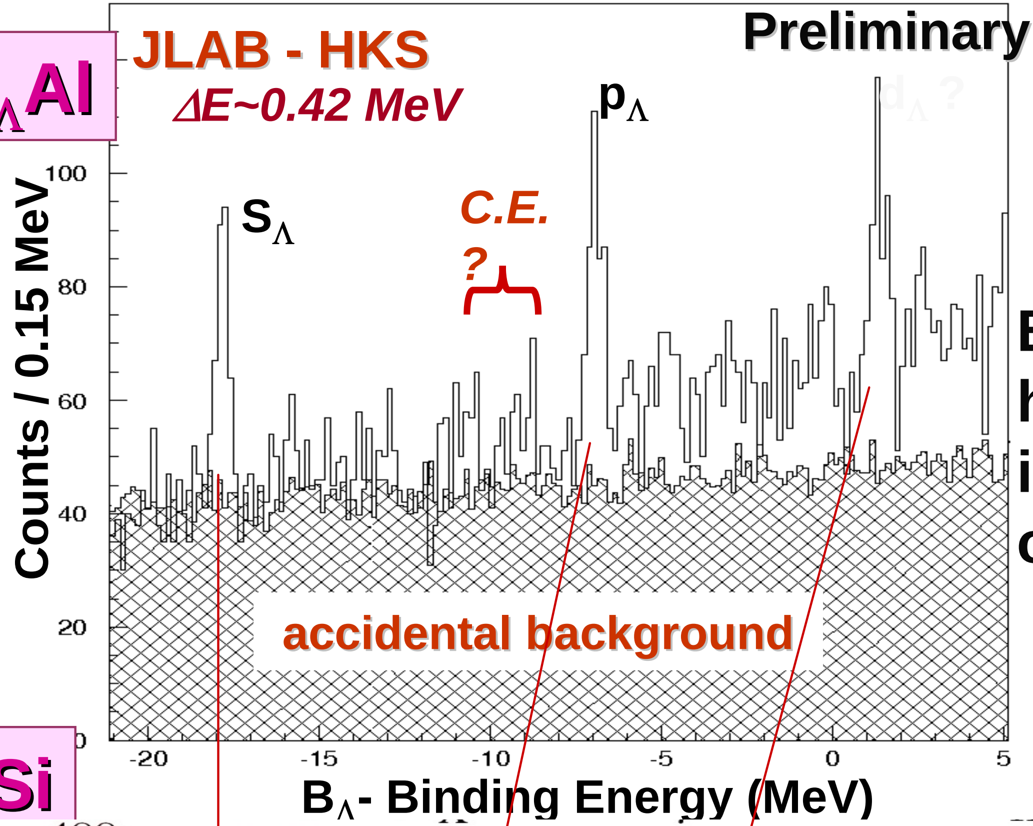
Enriched ^{28}Si target
100 mg/cm^2
30mA electron beam

^{28}Si (π^+,K$^+$) $^{28}_{\Lambda}$Si



$^{28}{}_{\Lambda}Al$ – spectroscopy by (e,e'K$^+$)

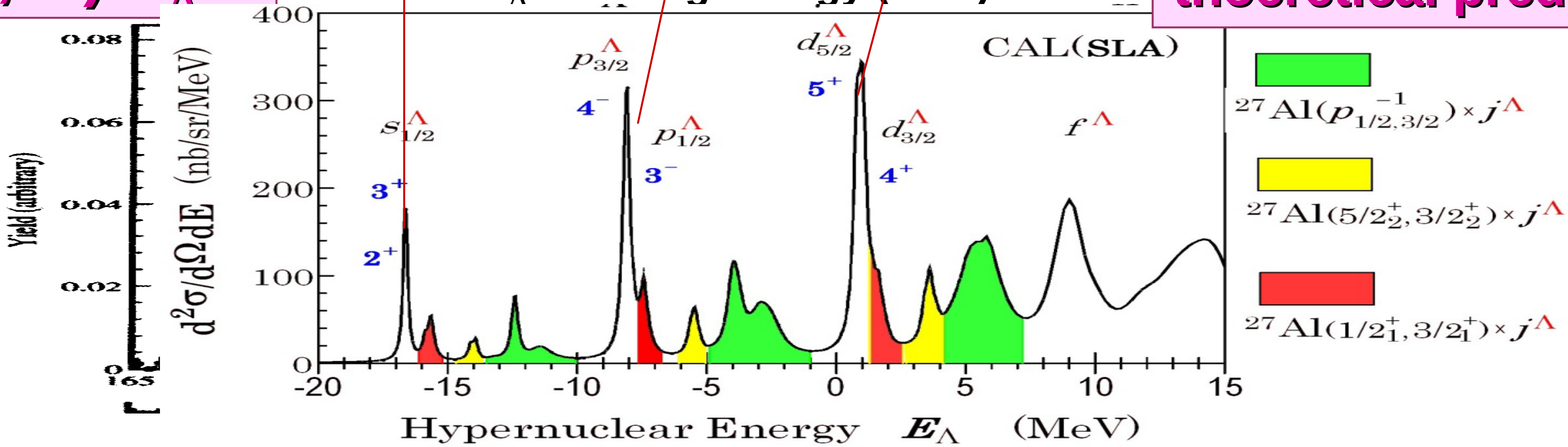
^{28}Si (e,e'K$^+$) $^{28}{}_{\Lambda}Al$



But applying to heavy hypernuclei is difficult because of e$^+$e$^-$ background.

^{28}Si (π^+,K$^+$) $^{28}{}_{\Lambda}Si$

thoeretical pred.

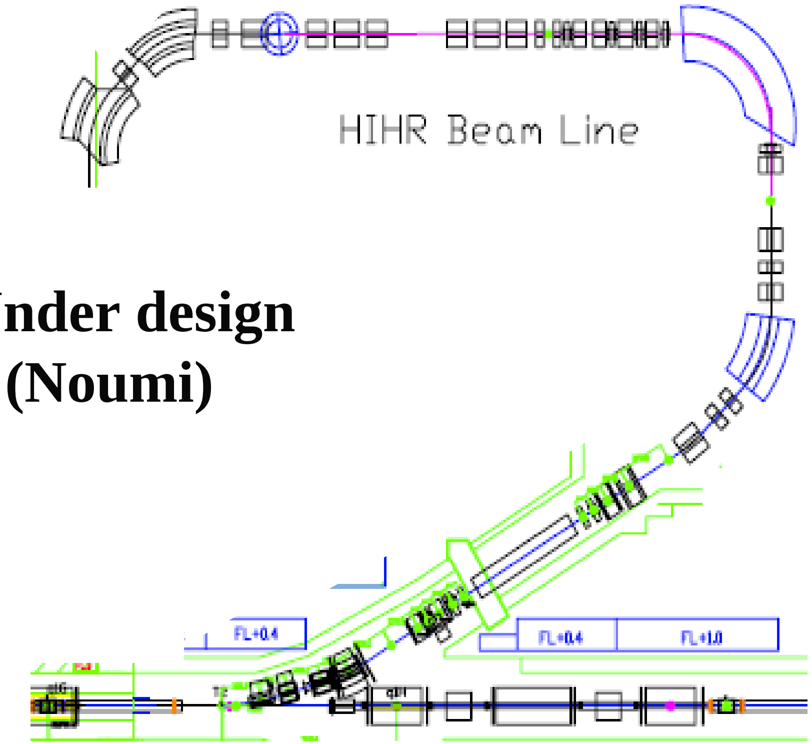


Hypernuclear Spectroscopy using High Resolution Pion Line

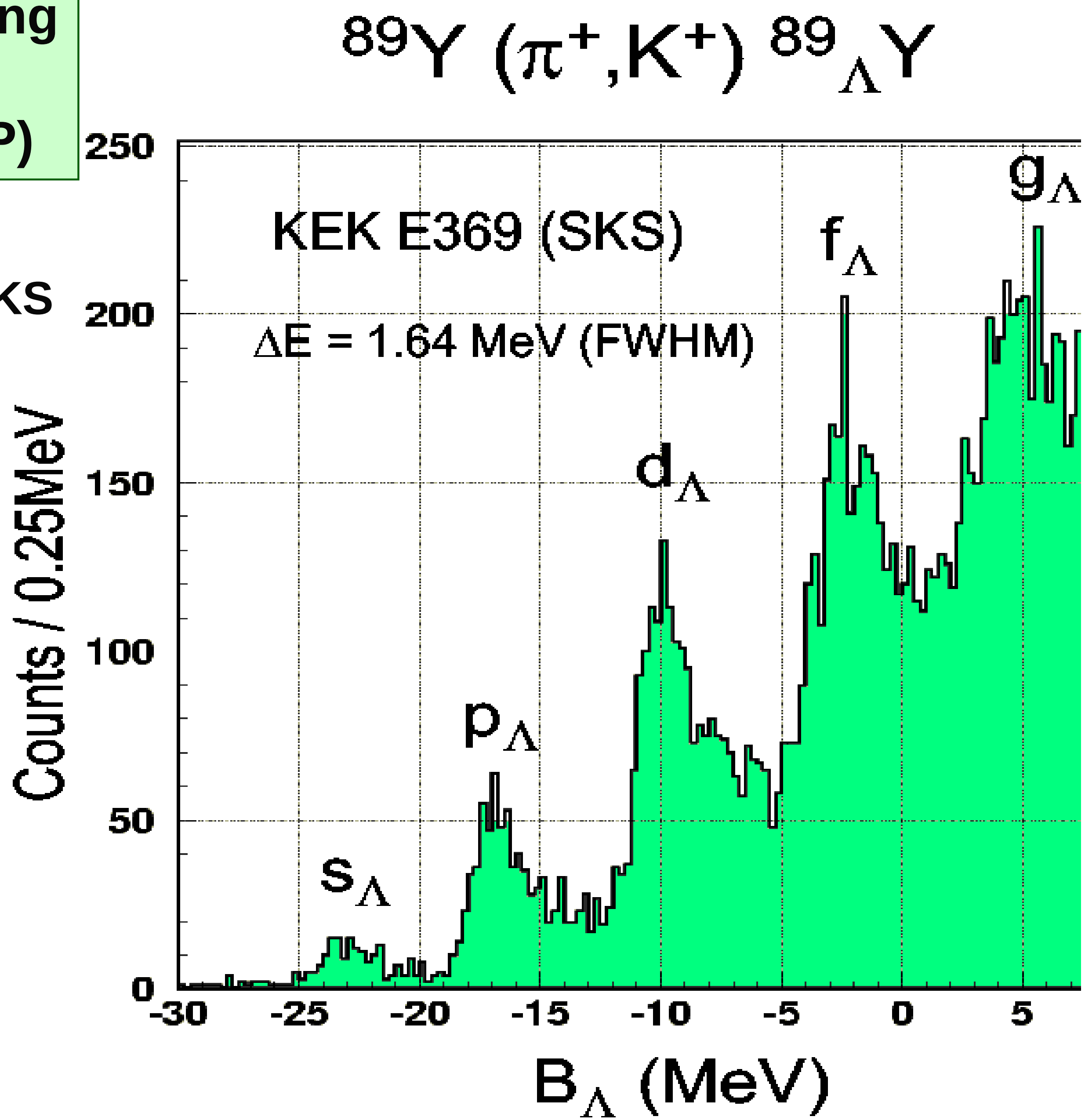
Momentum dispersion matching beam line
proposed by H. Noumi (RCNP)

ΔE = 0.2 MeV, 10^9 pions/s

← ΔE=1.5 MeV, 10^7 pions/s by SKS



Under design
(Noumi)



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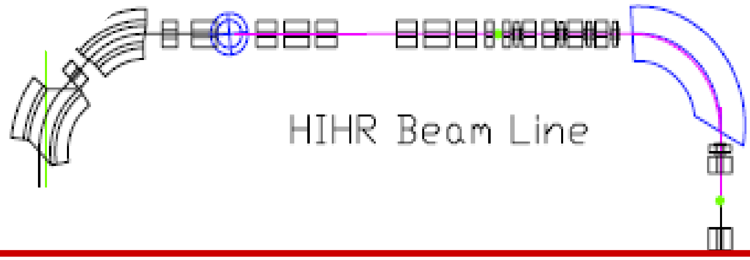
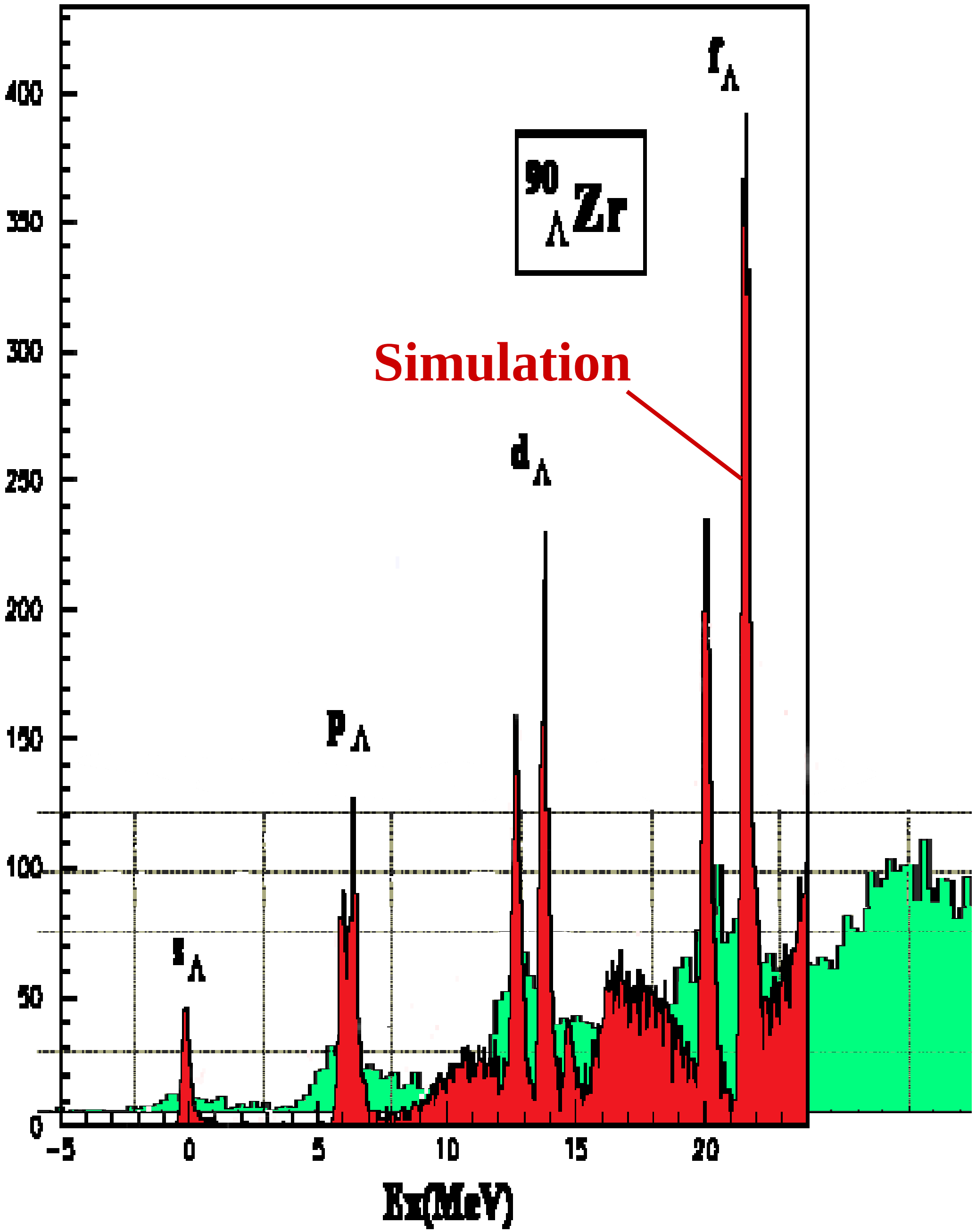


- Precise single particle energies and LS splitting of Λ hypernuclei
- n-rich Λ hypernuclei by (π^-,K^+)
- Σ hypernuclei (Coulomb assisted states) by (π^-,K^+)
- Weak decay and magnetic moment

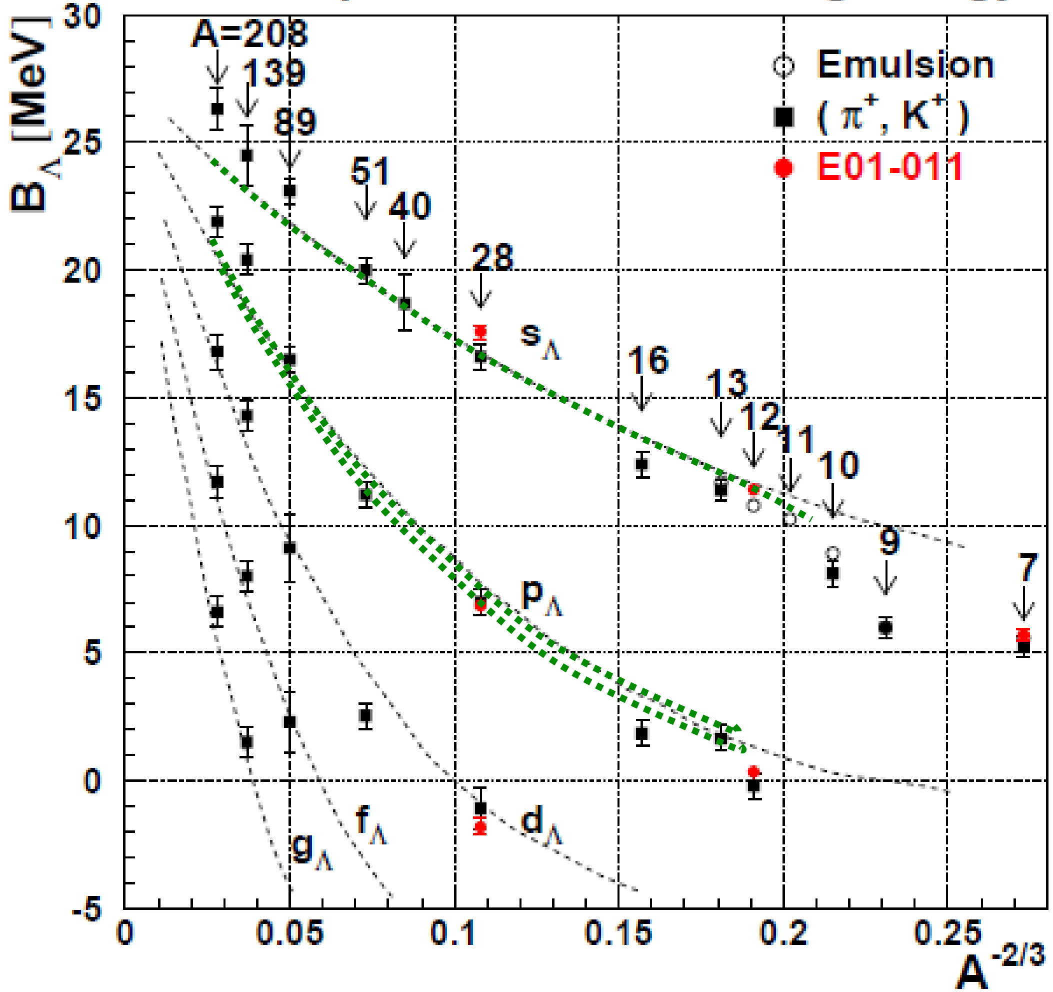


Single particle energy of Λ

Experimental data in future

- E(s_Λ, p_Λ, d_Λ, f_Λ,..) < 0.1 MeV accuracy (e,eK$^+$), high resol. (π^+,K$^+$)
- E(s_Λ) – E(p_Λ), E($p1/2_{\Lambda 1}$) – E($p3/2_\Lambda$) < 0.01 MeV accuracy
  γ spectroscopy for E1(p_Λ -> s_Λ)

Mass dependence of Λ binding energy



- Test of Bethe-Goldstone theory
  (Origin of single particle motion)
  m^*_N is not measurable, but m^*_Λ is.
  Understand effective interactions quantitatively
- Origin of nuclear LS splitting
  (2-body LS + tensor + ?)
- Probe hadron modifications in nuclear matter?
  (Baryons and bare nuclear forces may change in nucleus)
  – theoretical challenge

Summary

- **High-resolution γ spectroscopy has been applied to Λ hypernuclei with the dedicated Ge array, Hyperball / Hyperball2.**
- **Level schemes of most of the p-shell hypernuclei have been studied.**
- **The strengths of spin-dependent ΛN interactions have been derived and used to improve BB interaction models.
Most of the observed levels are well reproduced by these spin-dependent interaction strengths.**
- **The small tensor force strength (and ΣN–ΛN coupling effects) from level energy data agree with those predicted from Nijmegen BB interaction models. ΛN tensor force is small and unique.**
- **Precise data on Λ hypernuclear levels, particularly Λ's single particle energies, can be used to investigate the role of the tensor force, 3-body force, and LS force in the LS splitting and the nuclear structure. --- EGG OF IDEA? Need theoretical help.**