Hypernuclear Physics

An Overview on Hypernuclear Spectroscopy

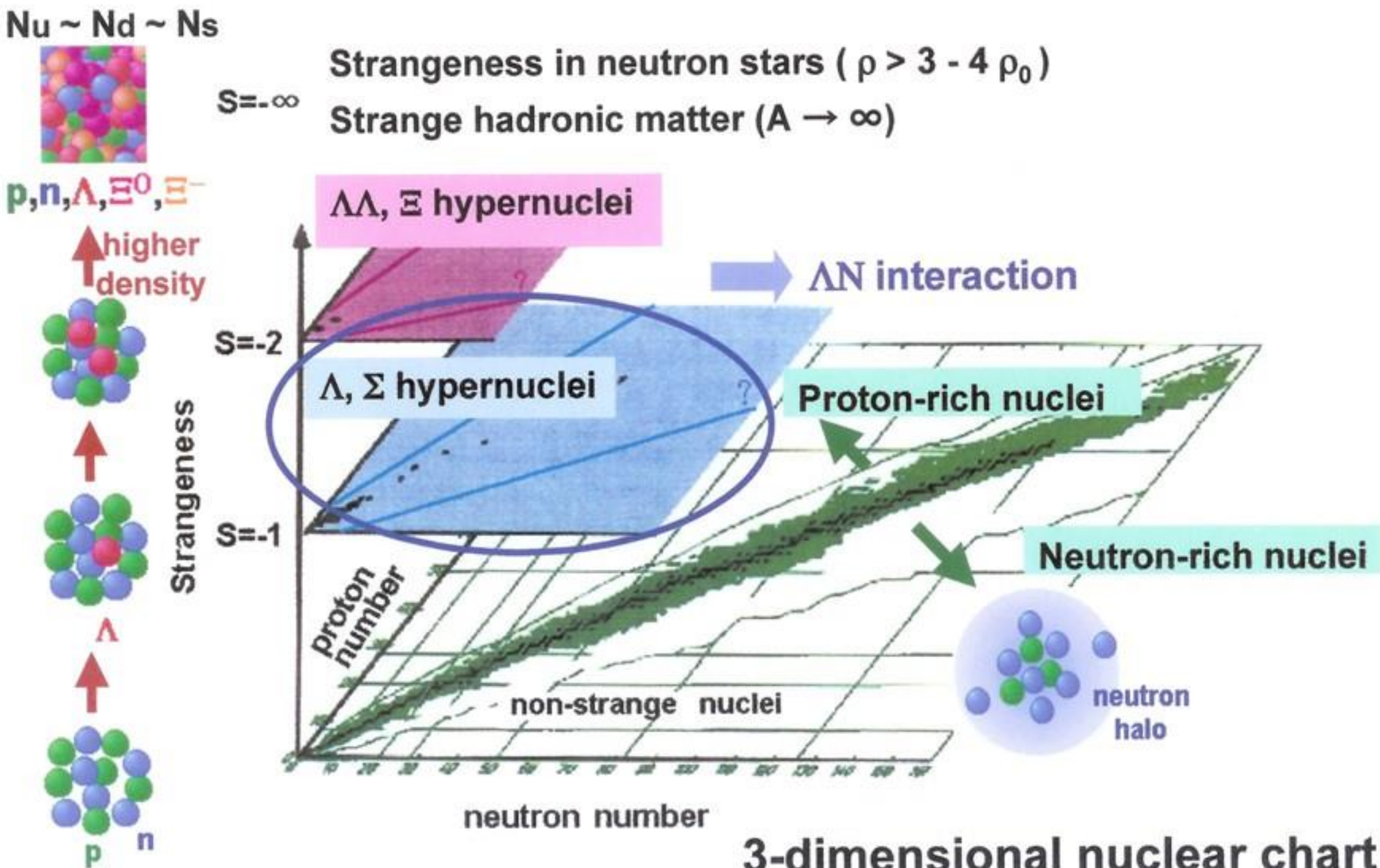
T. Motoba (Osaka E-C)

Workshop on J-PARC hadron physics
February 10-12, 2014, Tokai

CONTENTS

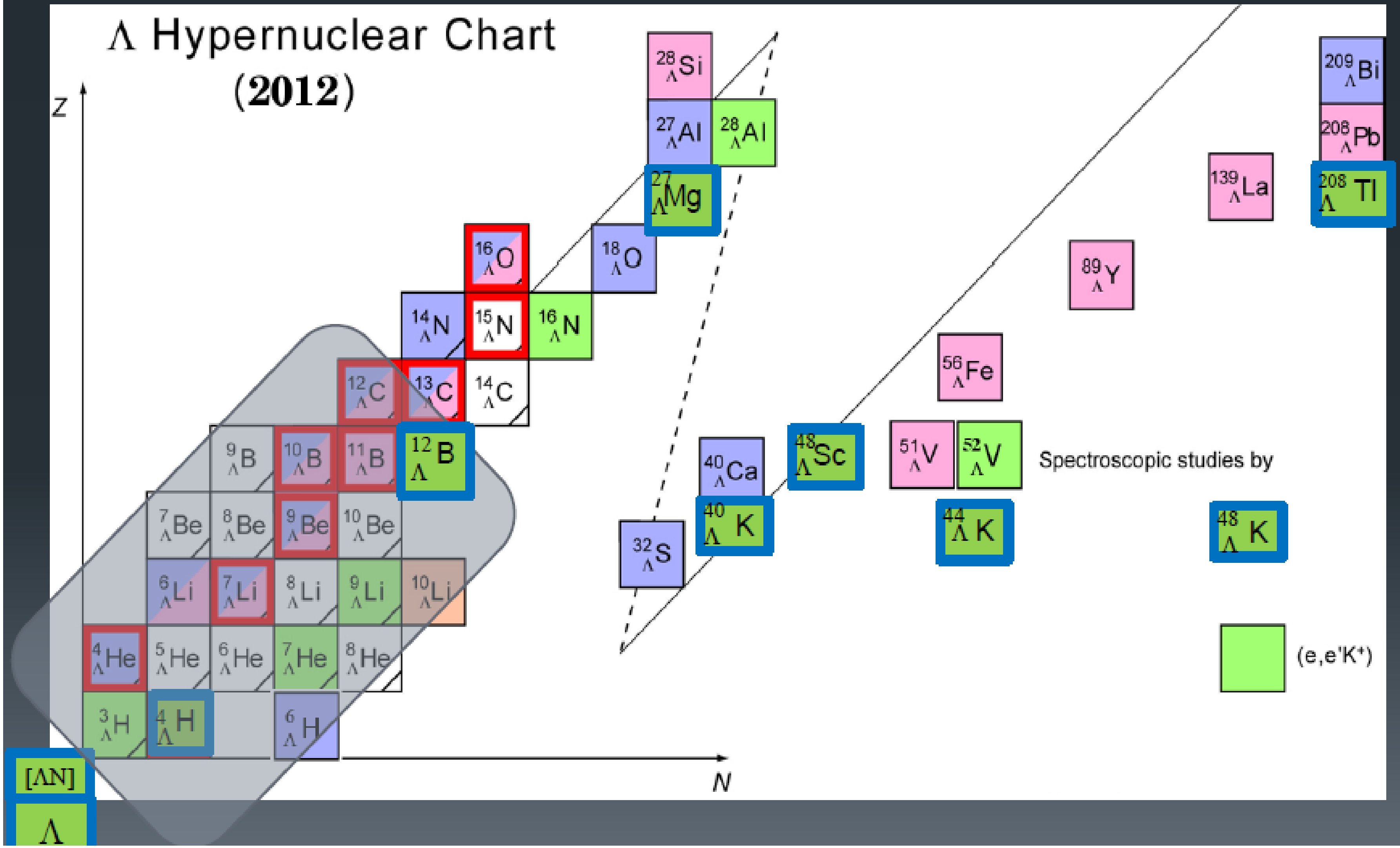
1. **Hypernuclear production process**
2. **Structure of Light hypernuclei and Y-N interaction properties**
3. **Prospects of medium-heavy hypernuclear production**
4. **New aspects observed/expected in strangeness many-body systems**
   - **4-1. shrinkage effects,**
   - **4-2. Appearance of genuinely hypernuclear states,**
   - **4-3. Coupling of Λ with nuclear collective motions such as rotation**
5. **Emphasize to compare different production proceses**
6. **Ξ-hypernuclei and double-Λ hypernuclei**

1. Hypernuclear production



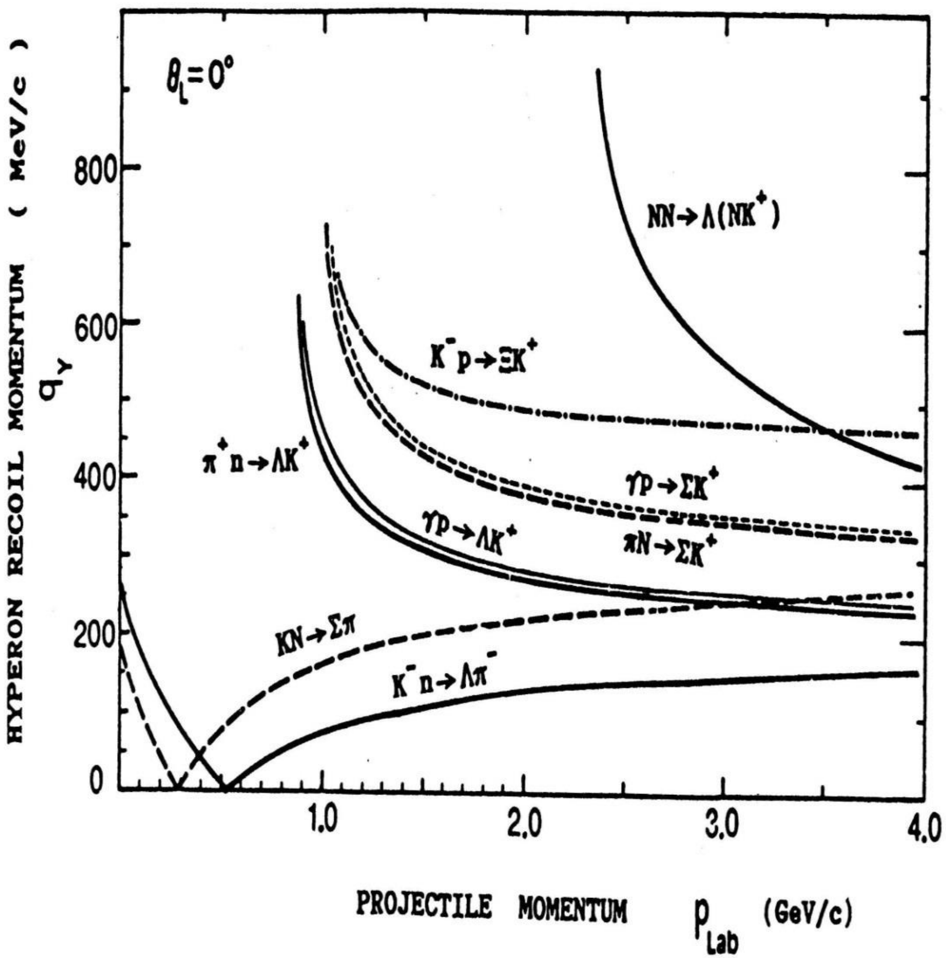
(From H. Tamura)

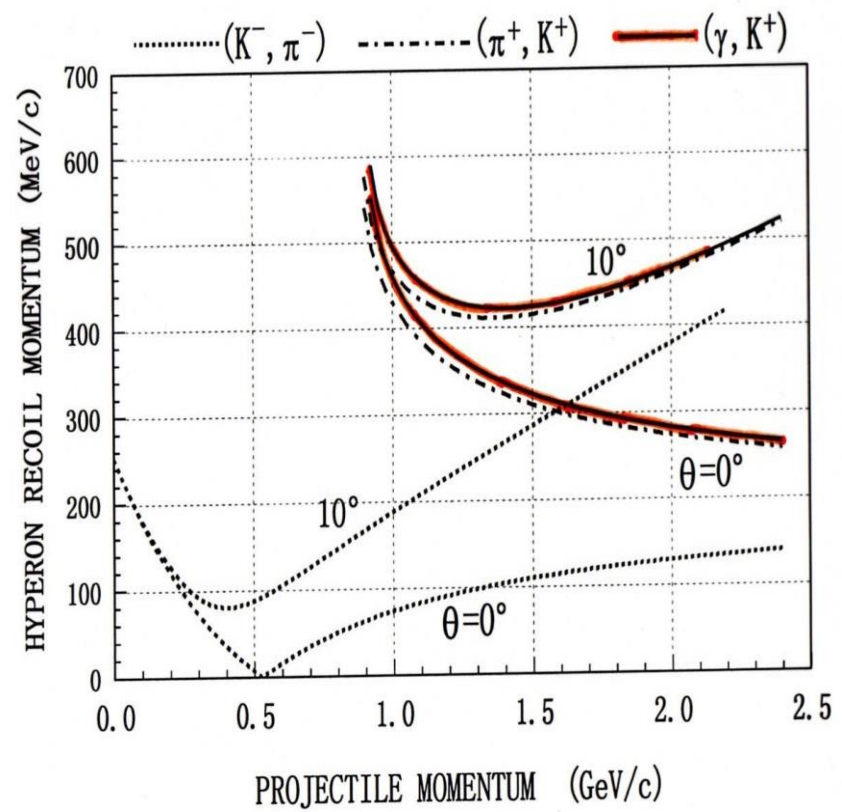
Hypernuclear Chart



Taken from N. Nakamura, based on O. Hashimoto and H. Tamura

Hyperon **recoil momentum** and the **transition operator** determine the reaction characteristics





q_Λ**=350-420** MeV/c at Eγ=1.3 GeV

Selectivity of hypernuclear production

(K^-,π^-) at p=0.8 GeV/c:

Recoilless production of Λ substitutional states with ΔL=0,1

(π^+,K^+) at p=1.05 GeV/c:

Natural parity high-spin stretched states

$(e,e'K^+)$, (γ,K^+) at p=1.3 GeV/c:

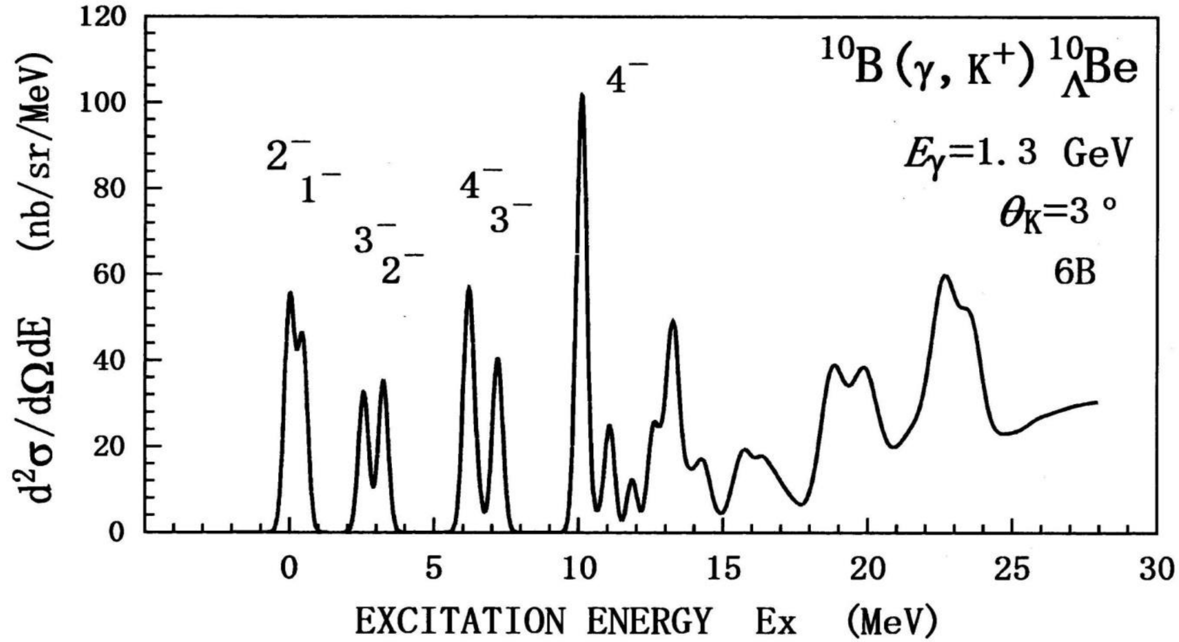
Unnatural parity high-spin states

Typical example

^{10}B target:

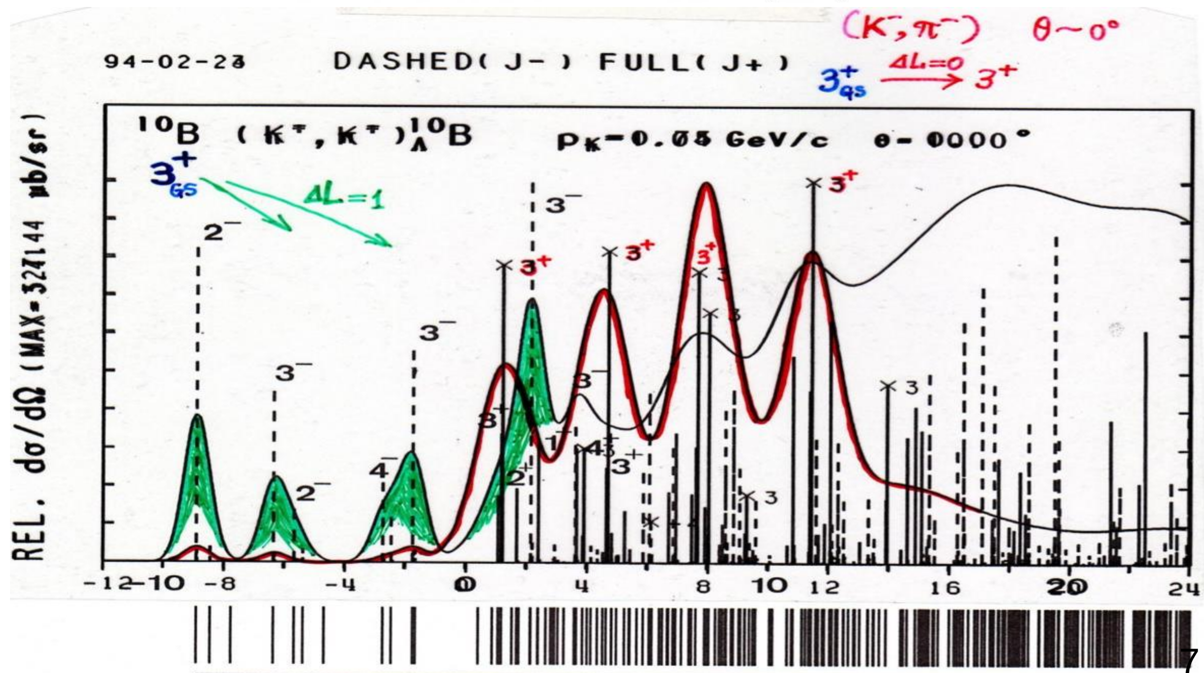
All Predictions

Motoba-Sotona-Itonaga, P.T.P. Suppl.**117** (1994)

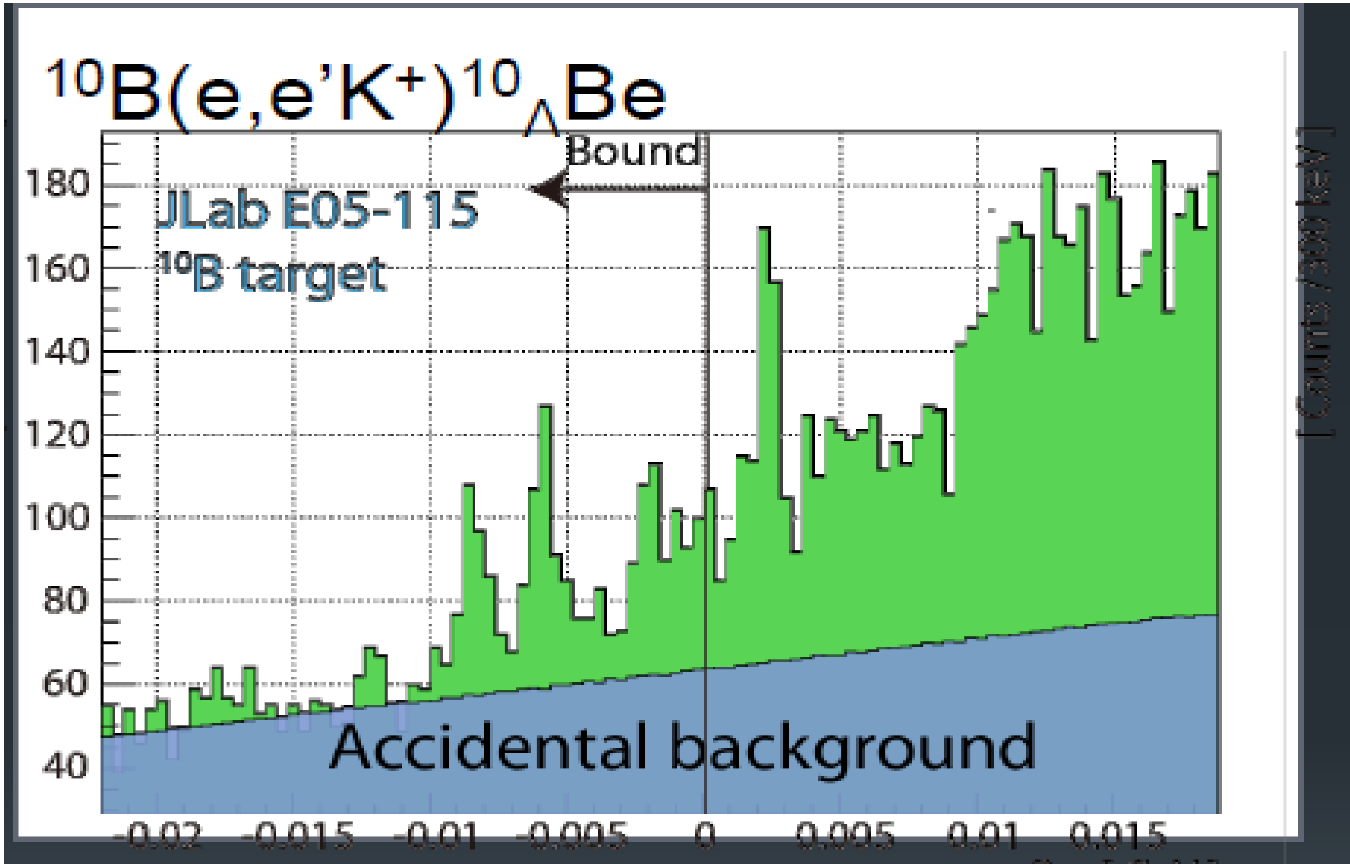


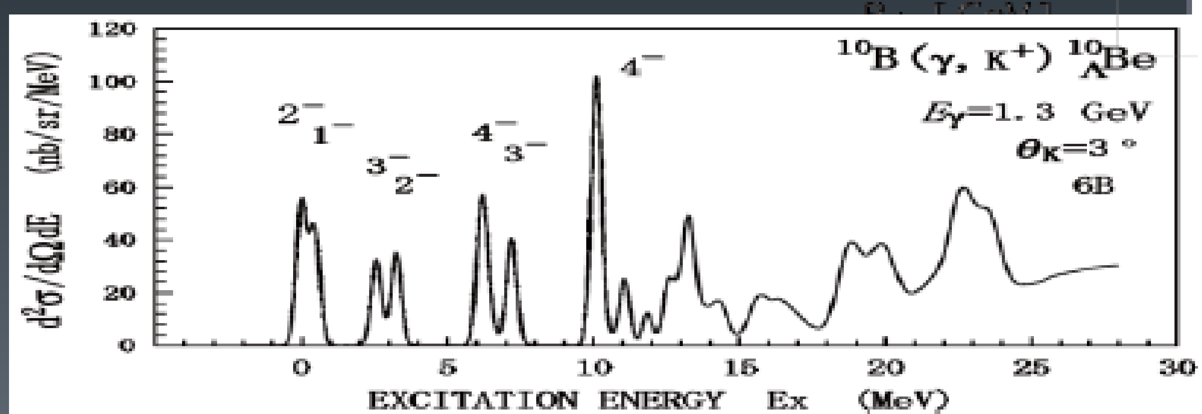
compared with

other theoretical calculations for
(K-,π-)
(π+,K+)



EXP from JLAB, (2009,Nakamura)





CAL (1994)

2. Structure of light hypernuclei and Λ-N interaction properties

Three factorse

(1) p-shell hypernuclei: detailed shell-model calculations have been performed.

- Two-body ΛN effective interaction

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

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

Δ $\quad S_\Lambda$ $\quad S_N$ $\quad T$

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

(2) Cluster-model calculations have been performed extensively by several authors also
for light p-shell hypernuclei:

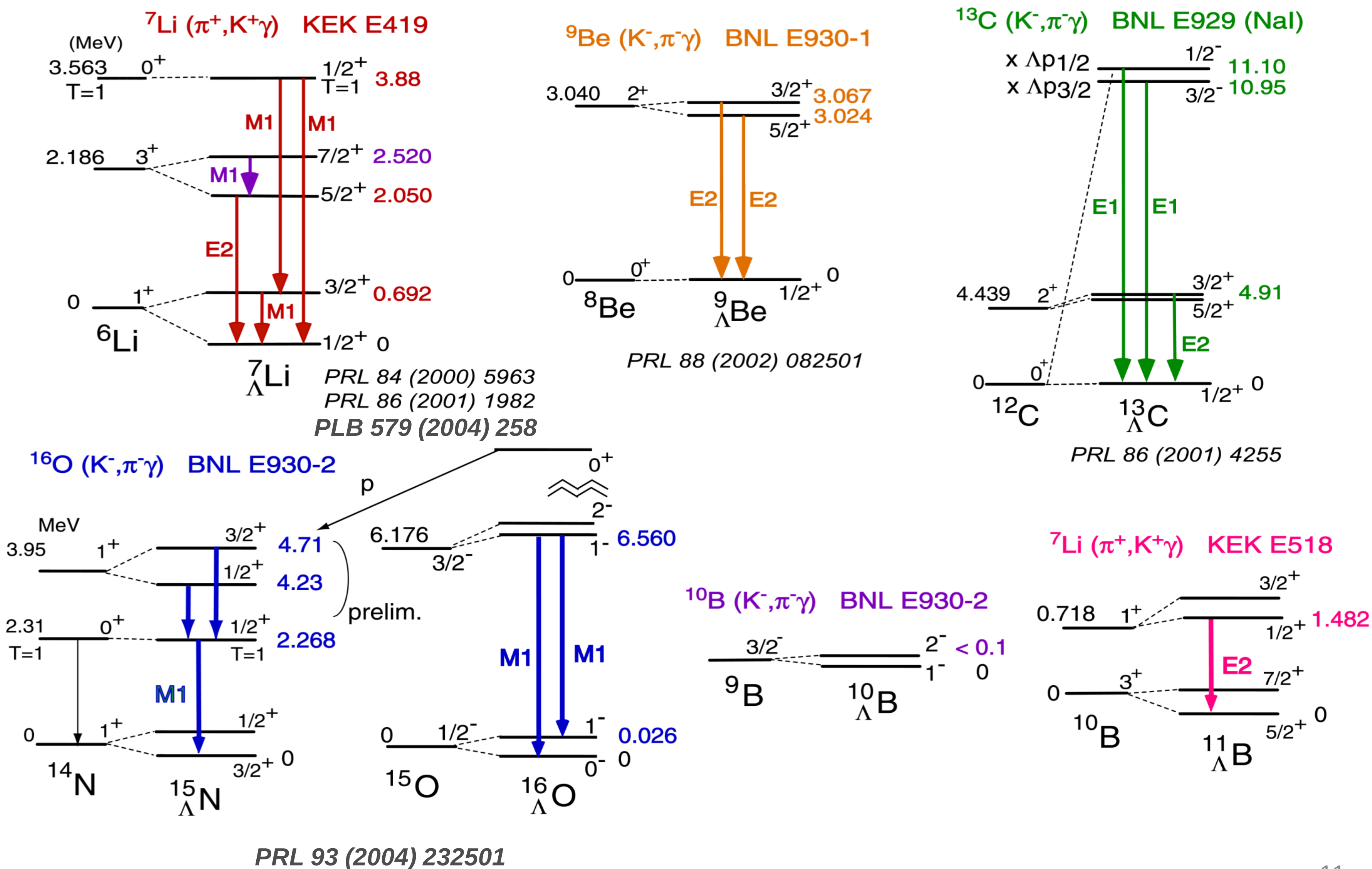
Microscopic α + x + Λ model (x= p,n,d,t,h,α)

(3) After all progress of experiments with "Hyperball"
High-resolution γ–ray measurements have been done successfully in p-shell region

→

σ.σ and spin-orbit interactions have been deduced

High-resolution γ-ray measurements (H. Tamura et al.)



Spin dependence: remarkable differences in $V_{\Lambda N}$

Comments:

Repulsion due to strange-meson exchange (K, K^*, K) is weak

- Odd state { ND -------- strongly attractive (−40.5 MeV); others -------- vanishing or repulsive }
- Even state { NSo ------- $^3S_1$ attraction: too small; others -------- the sums are similar. ($^1S + {}^3S$) }

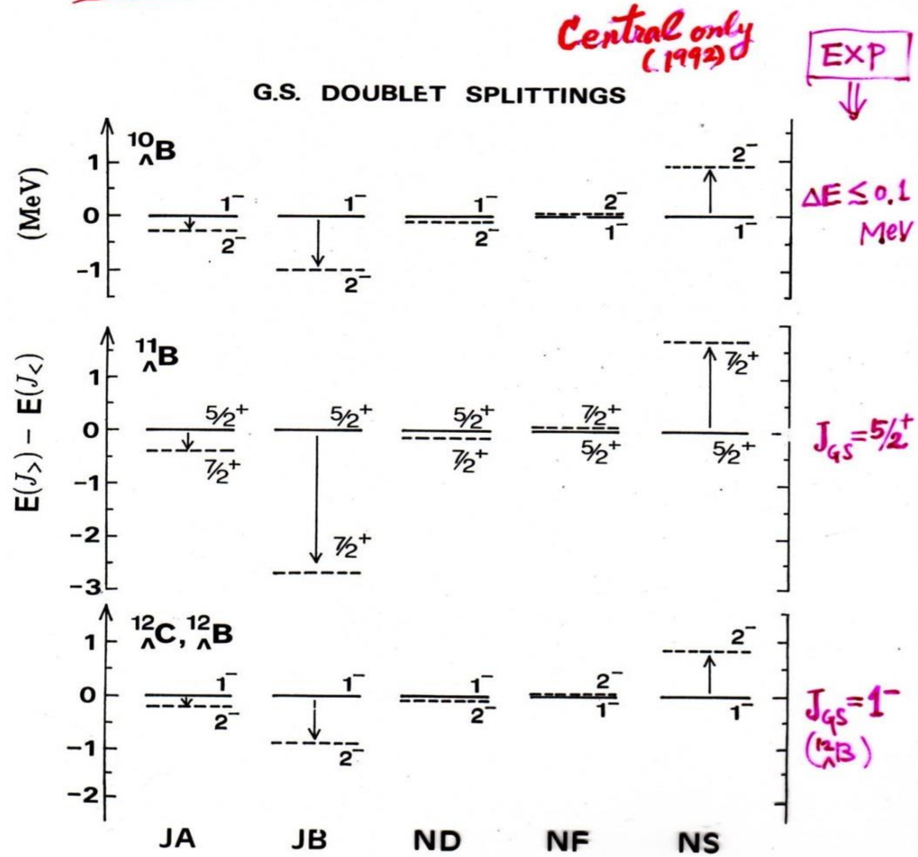
NS = NSo + (s.p. potential in the intermediate state)
↳ This gives rise to strengthen ^3S because of the strong ΛN-ΣN coupling in NS

- $|{}^1S_0| \ll |{}^3S_1|$ in JA, JB
- TOTAL U_Λ : JA ≈ JB ≈ NF ≈ NS

However, singlet/triplet ratios differ very much from each other.

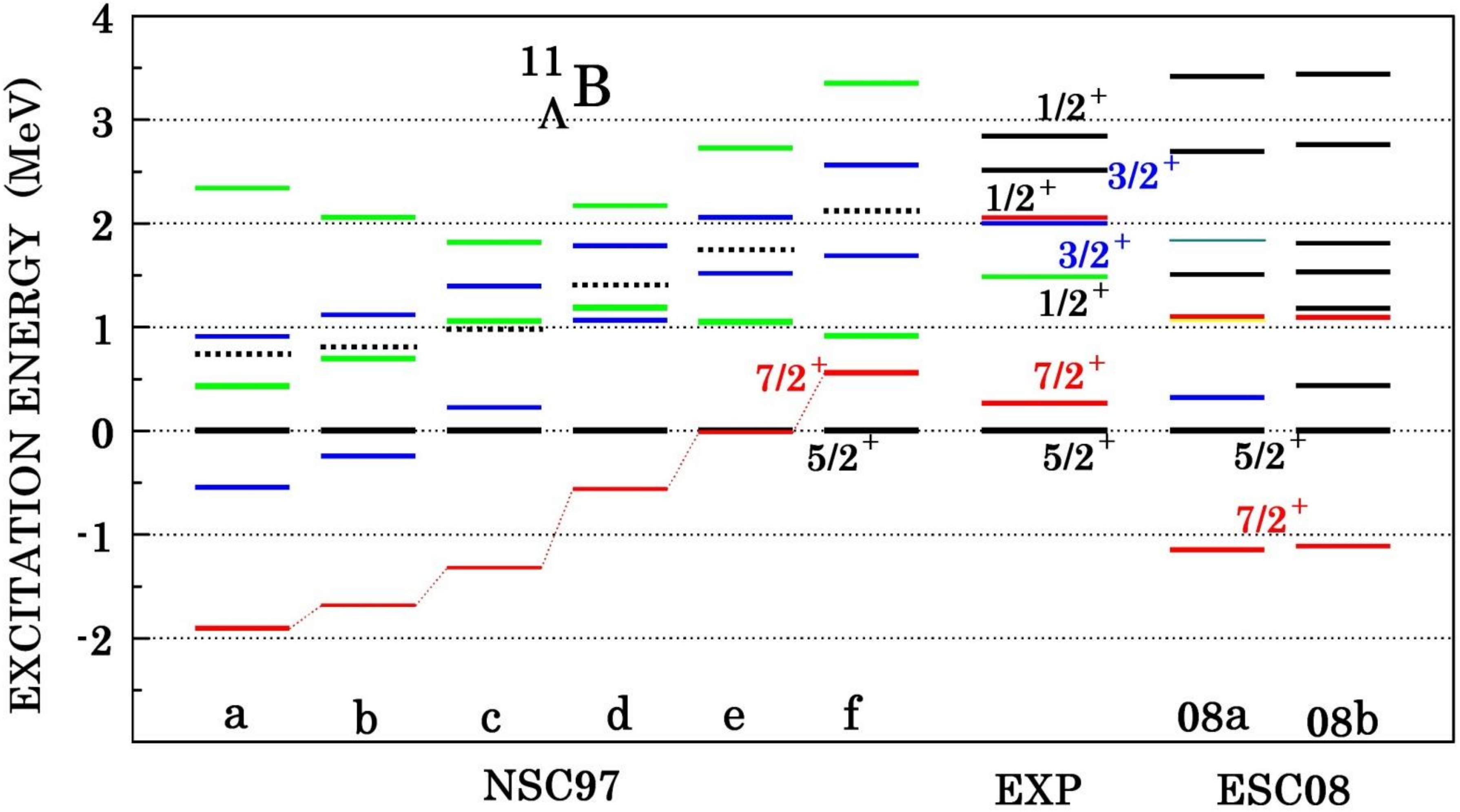
	JA		JB		ND		NF		NS
$R_{13} \equiv \frac{(S=1)}{(S=3)} =$	$\frac{1}{7.6}$	:	$\frac{1}{68.8}$	:	$\frac{1}{3.4}$	:	$\frac{1}{2.0}$	:	$\frac{1}{0.9}$

Difference in spin-spin force

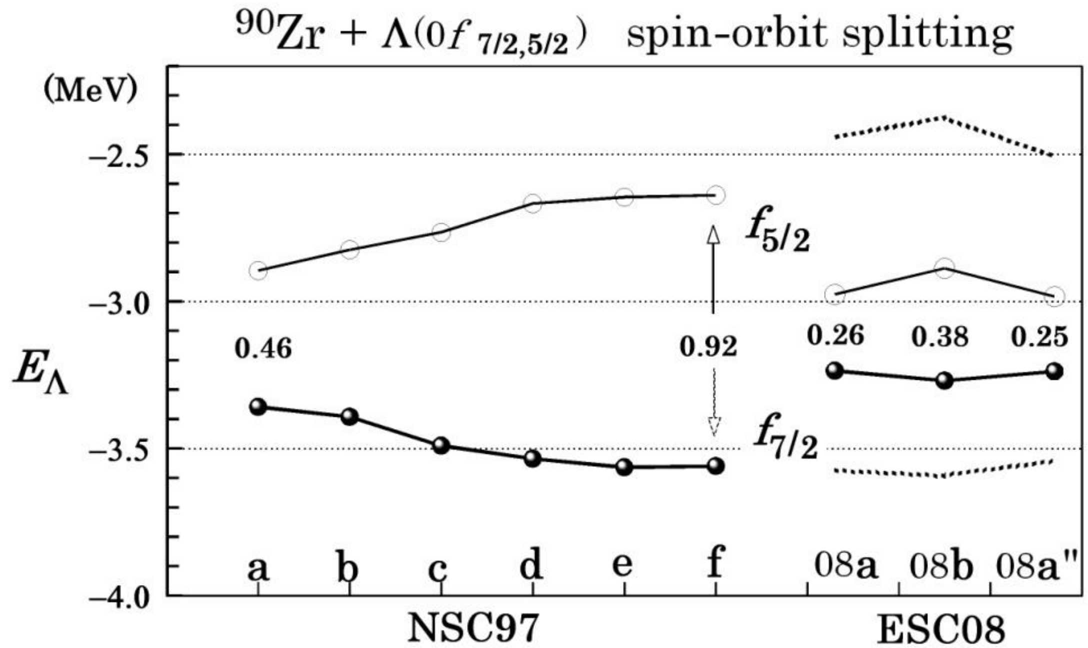


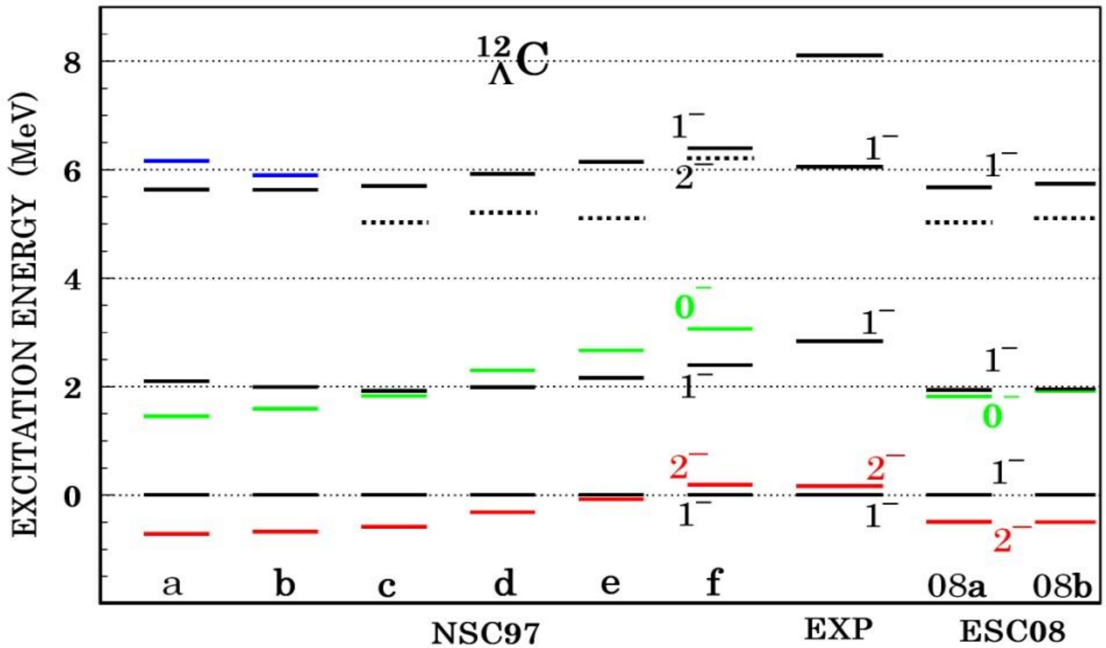
{ $J_<$ is dominated by $^1S_0$.
$J_>$ is dominated by $^3S_1$. }

Nijmegen B-B interaction model improved by taking account of hypernuclear data



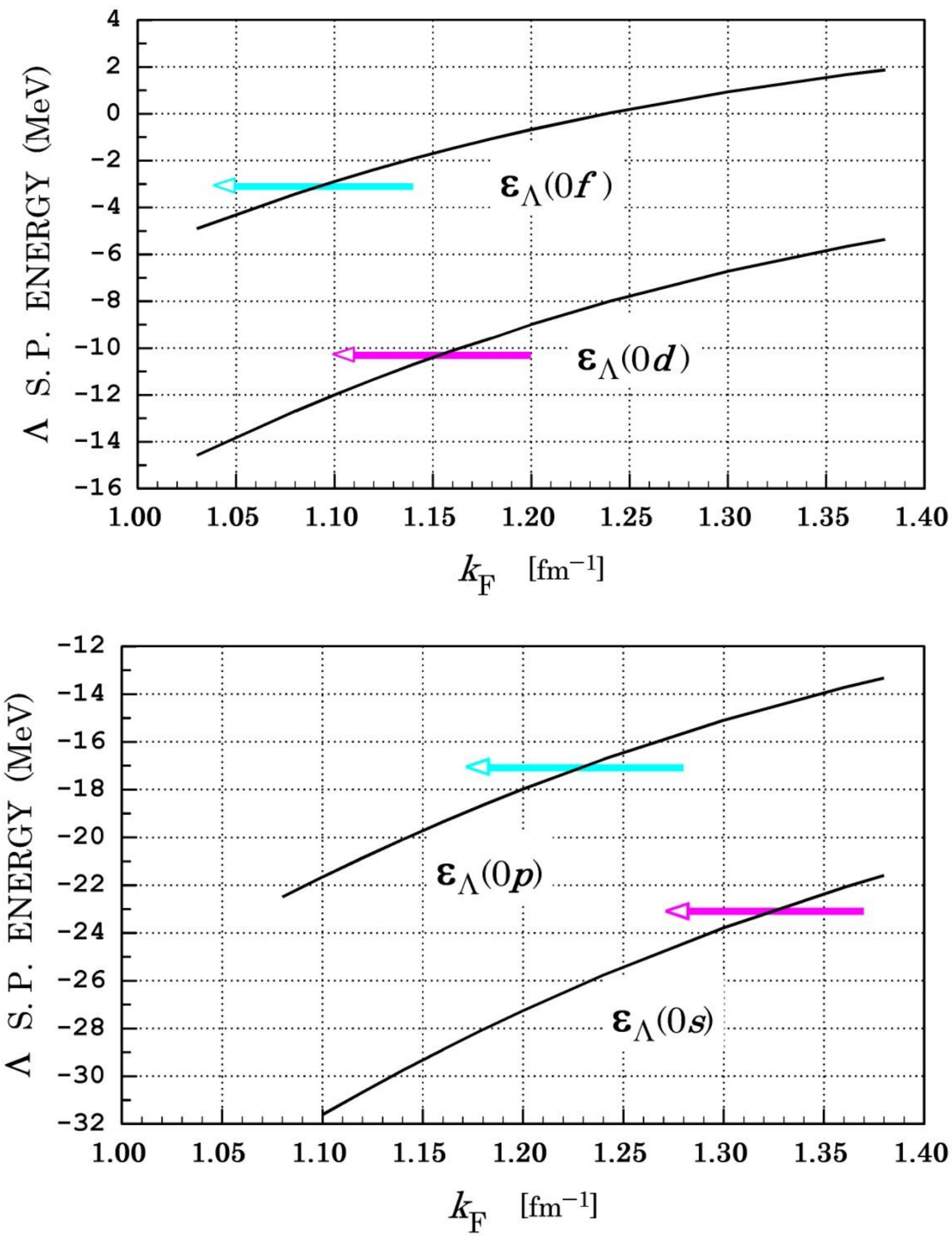
Spin-spin and spin-orbit splitting at A=90



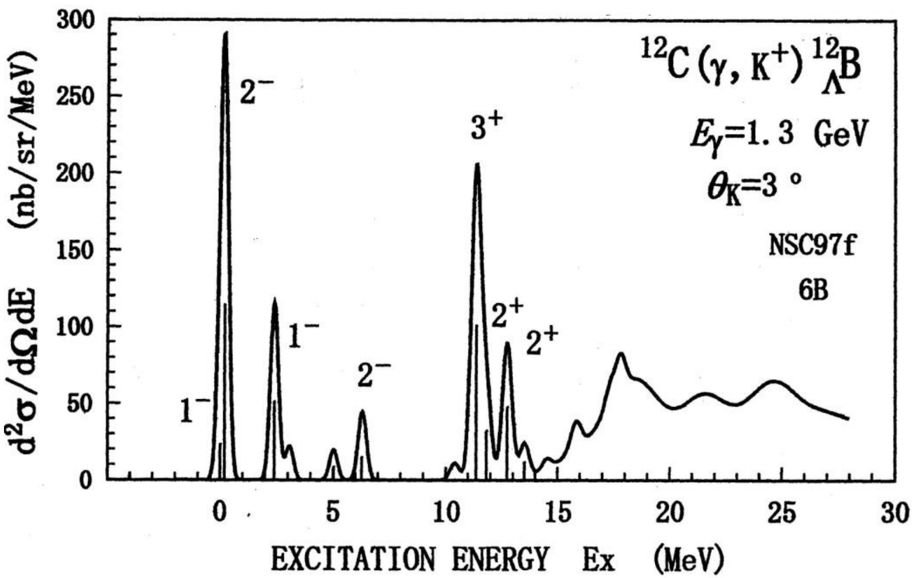


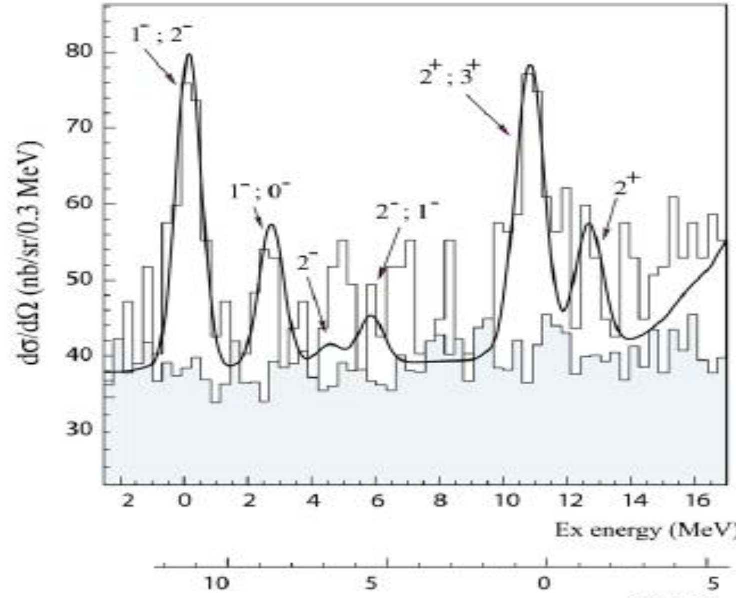
Density dependence of Nijmegen NSC97f model

(YNG-type effective interaction)



Elem. ampl. Theor. prediction vs. (e,e'K$^+$) exp.

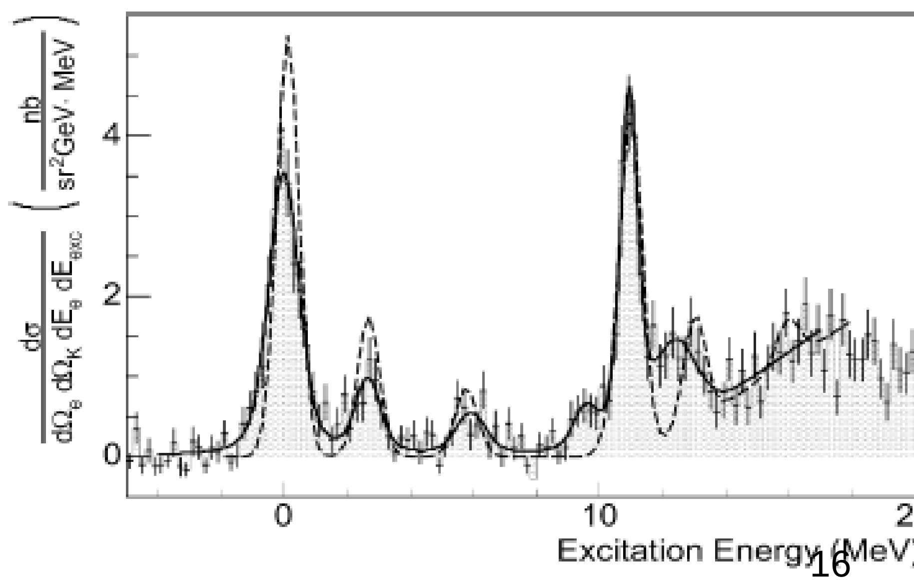




Motoba. Sotona, Itonaga,
Prog.Theor.Phys.Sup.**<u>117</u>** (**1994**)
T.M. *Mesons & Light Nuclei* (2000)
updated w/NSC97f.
-------------------- Sotona's Calc.----→

Hall C (up) T. Miyoshi et al.
*P.R.L.***90** (**2003**) 232502. **Γ=0.75 MeV**

Hall A (bottom), J.J. LeRose et al.
N.P. A**804** (**2008**) 116. **Γ=0.67 MeV**



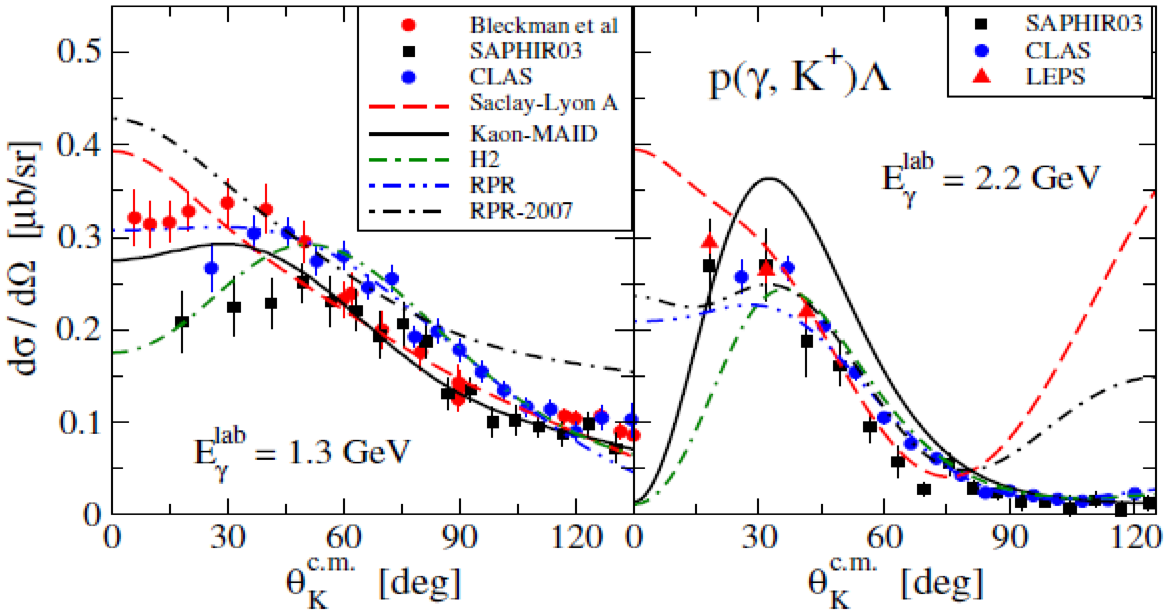
Possible test of $\gamma p \to \Lambda K$ ampl.

Comparison of isobar and Regge-plus-resonance models

H2: isobar model with hadronic f.f.; fit to CLAS data; nucleon resonances: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1895)$; hyperon resonances: $S_{01}(1670)$, $S_{01}(1800)$

RPR: fit to CLAS and LEPS data (cross sections) with resonances $S_{11}(1535)$ $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1895)$; multidipole-Gauss hadronic f.f.;

motivated by RPR-2011B [Lesley De Cruz, PhD thesis, Ghent University, 2011]



RPR-2007:
Corthals et al, 2007,
version RPR-2+D13

P.B., M. Sotona, Nucl. Phys. A 835 (2010) 246

(From P. Bydzovsky)

Theor. vs. Exp. → Test of elem. Ampli.

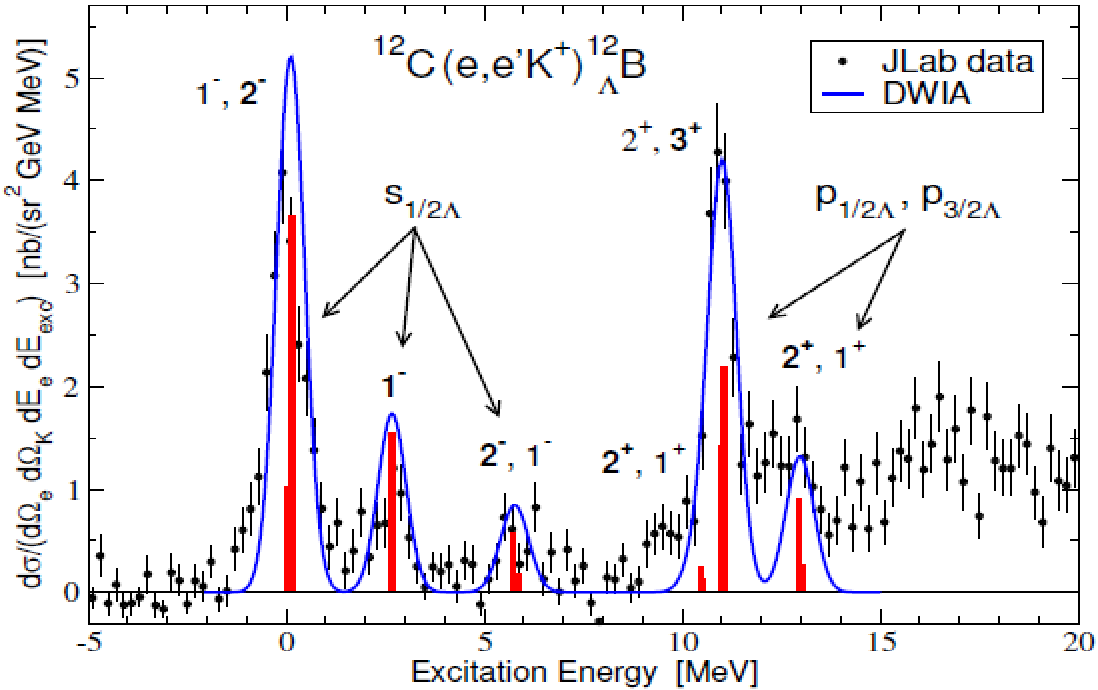
A possible test of models at forward angles

DWIA calculation of the cross sections for the electroproduction of hypernuclei

M. Sotona, S. Frullani, Prog. Theor.Phys.Suppl.117(1994)151

elementary amplitude: Saclay-Lyon A

JLab data E94-107: W= 2.2 GeV, Q^2=0.07 $(GeV/c)^2$



M.Iodice,...M.Sotona,...
Phys.Rev.Lett.99(2007)052501

E_x (MeV)	cross sections ($nb/st^2/GeV$) Exp.	Theor.
0.0	4.48±0.29	4.68
2.65	0.75±0.16	1.54
5.92	0.45±0.13	0.76
10.93	3.42±0.50	3.98

P. B., M. Sotona, Nucl. Phys. A 835 (2010) 246

3. We need high resolution data for medium-heavy hypernuclei to make serious test of Λ-N interaction properties

In heavier mass region only $^{89}Y(\pi+,K+)$ case seem to provide good-energy resolution data.

Cf. energy resolution

(K$^-$,π^-)

Γ = 3-4 MeV

(π^+,K$^+$)

played a great role of exciting high-spin series

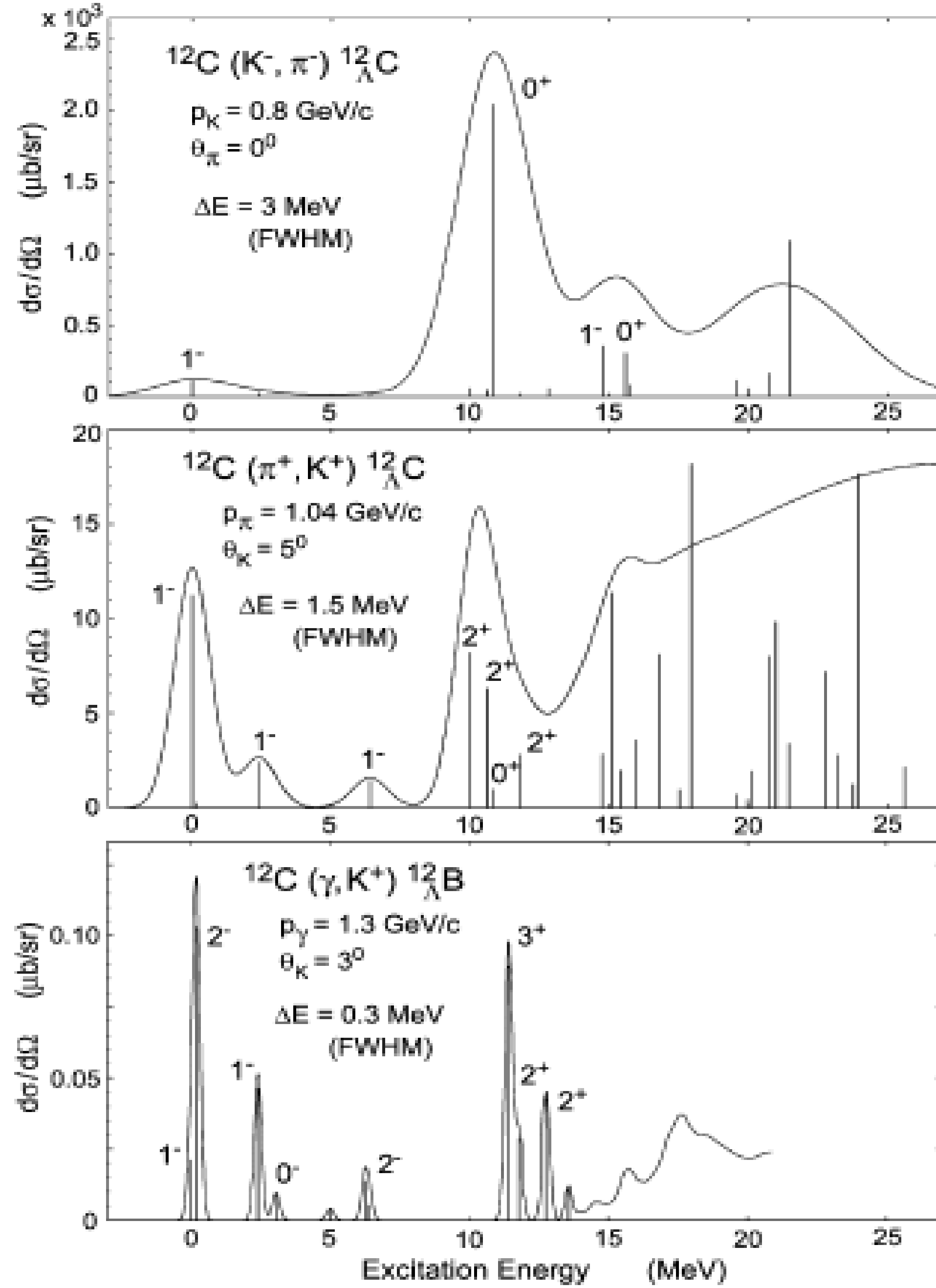
Γ = 1.5 MeV (best)

(e,e'K$^+$), (γ, K$^+$)

Motoba. Sotona, Itonaga, Prog.Theor.Phys.S.**117**(1994)

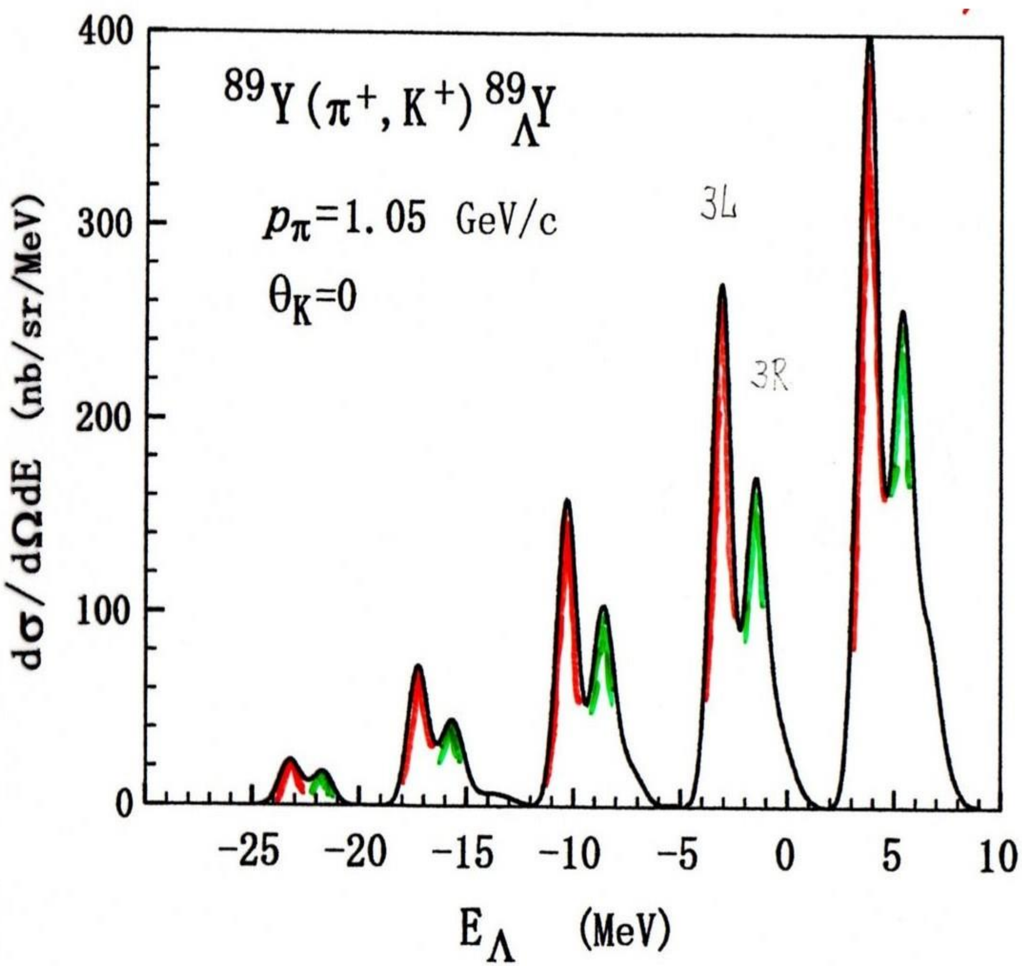
T.M. Mesons & Light Nuclei (2000) updated w/NSC97f.

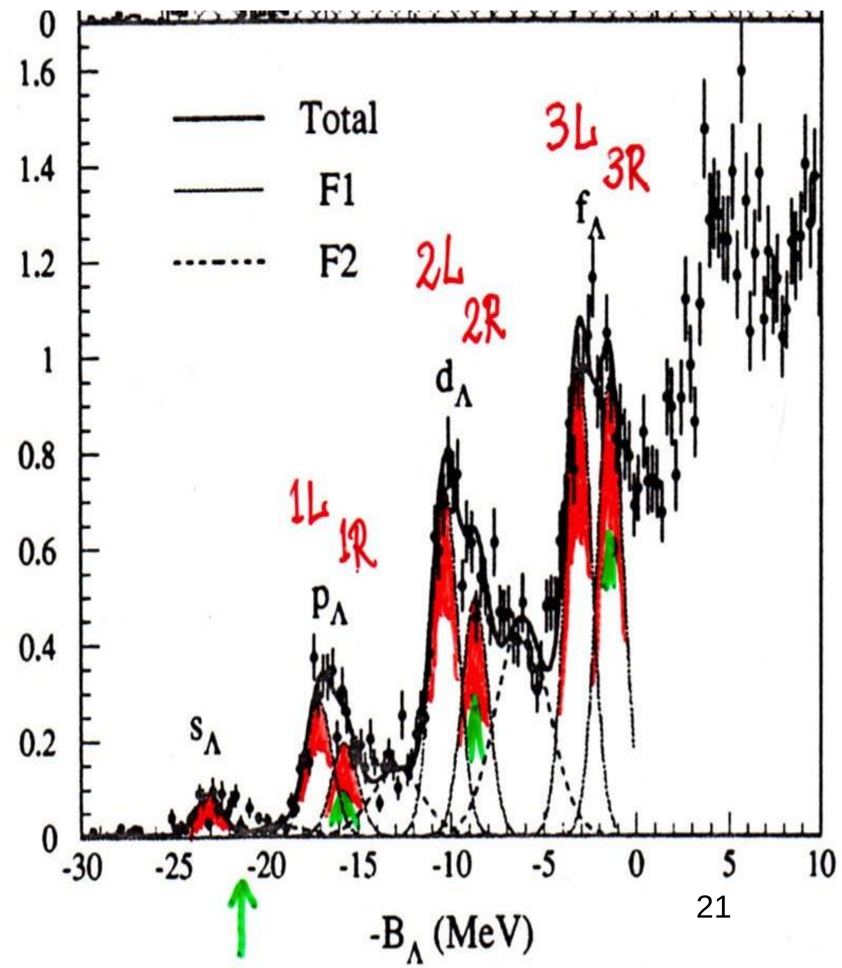
JLab Exp't : Γ = 0.5 MeV



DWIA analysis with core-excitation

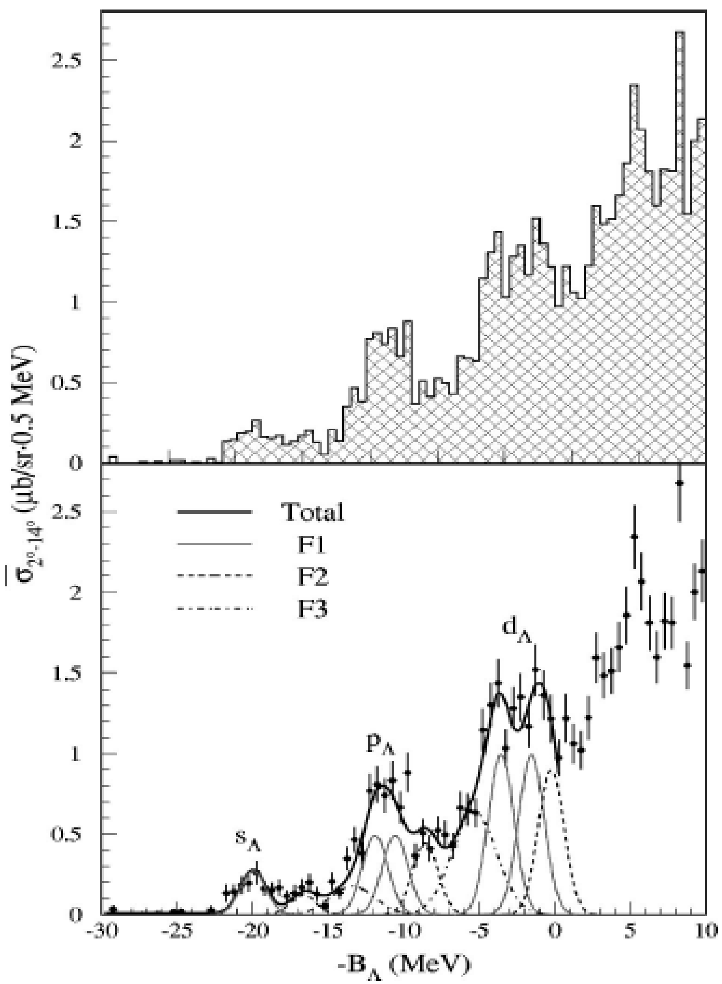
reproduces cross section ratios among a series of pronounced peaks and sub-peaks.





Left : Hotchi et al., PRC 64 (2001) ${}_{\Lambda}^{51}V$, ${}_{\Lambda}^{89}Y$,
Right:Hasegawa et al., PRC 53 (1996) ${}_{\Lambda}^{139}La$, ${}_{\Lambda}^{208}Pb$

H. HOTCHI *et al.*



1216 T. HASEGAWA *et al.*

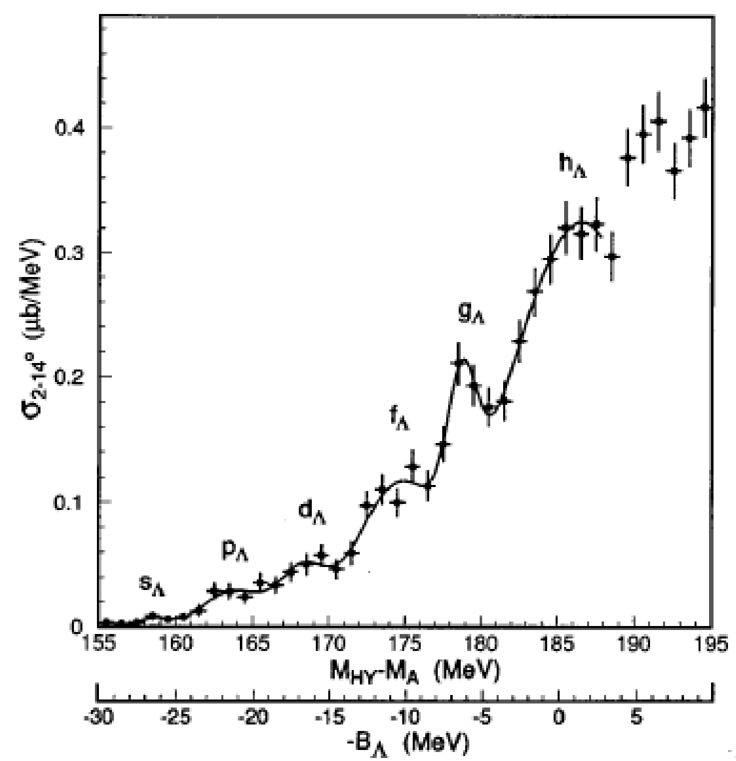
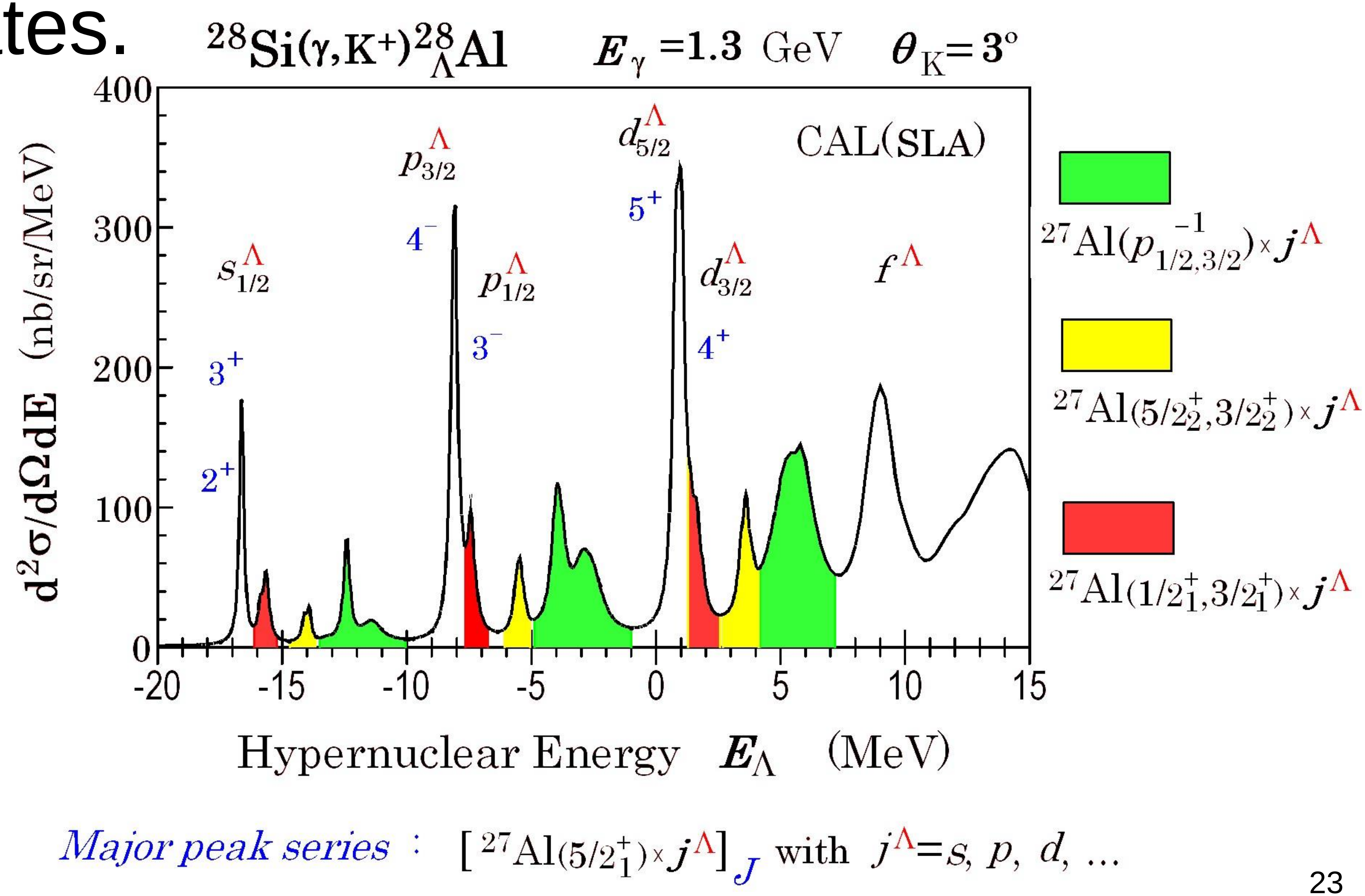


FIG. 10. Hypernuclear mass spectrum of ${}_{\Lambda}^{208}Pb$ with a fitting curve described in the text.

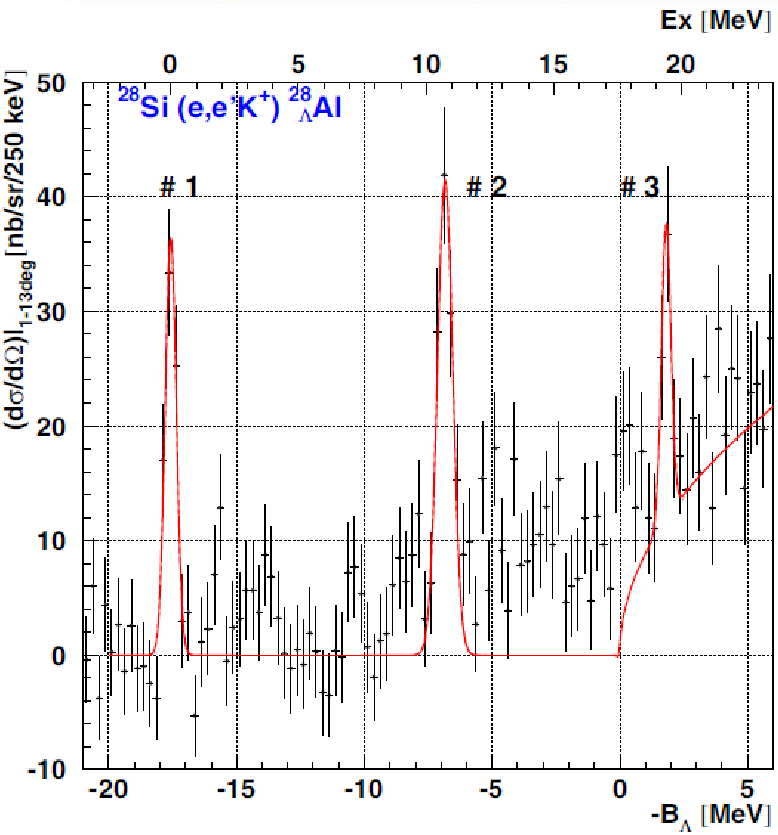
gions. T
0.006 μ
the same
data. Th
0.01 μb
ground
by the t
assumed
fitting.

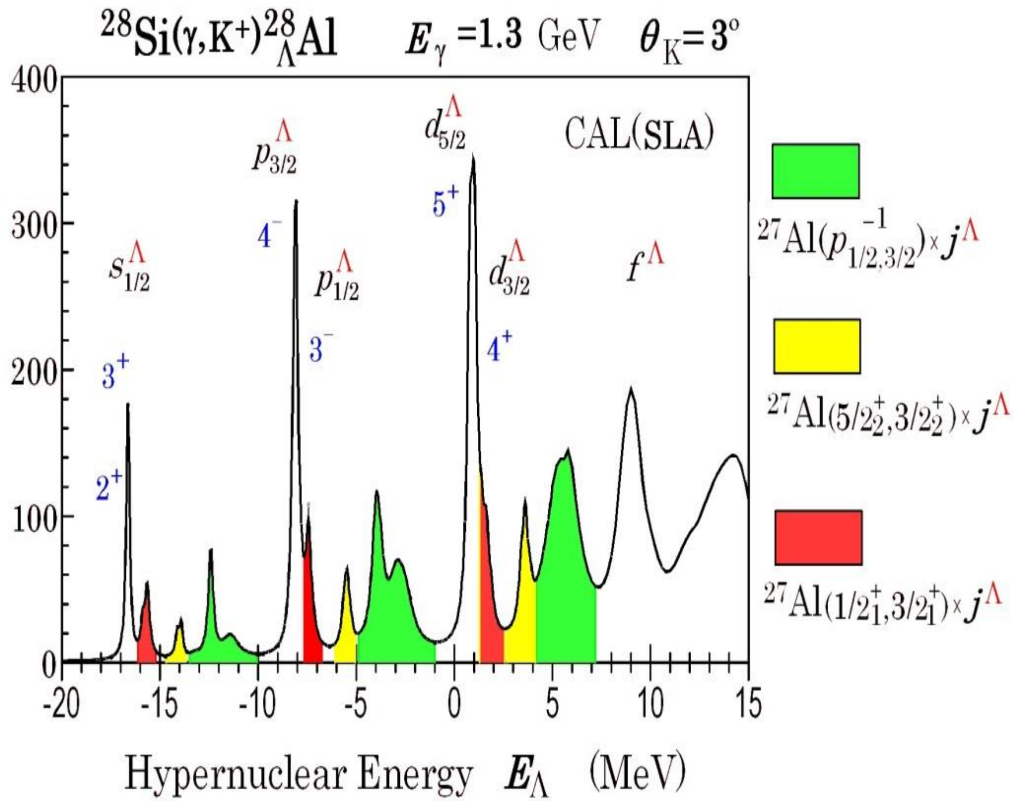
The
B_Λ=11
two la
$(\pi^+, K^+$
neutron-
$[0p_{3/2}^{-1}$
was sho
[15].
The
though
was dis
coupling

Spin-flip dominance leads to selective excitation of high-spin unnatural parity states.



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





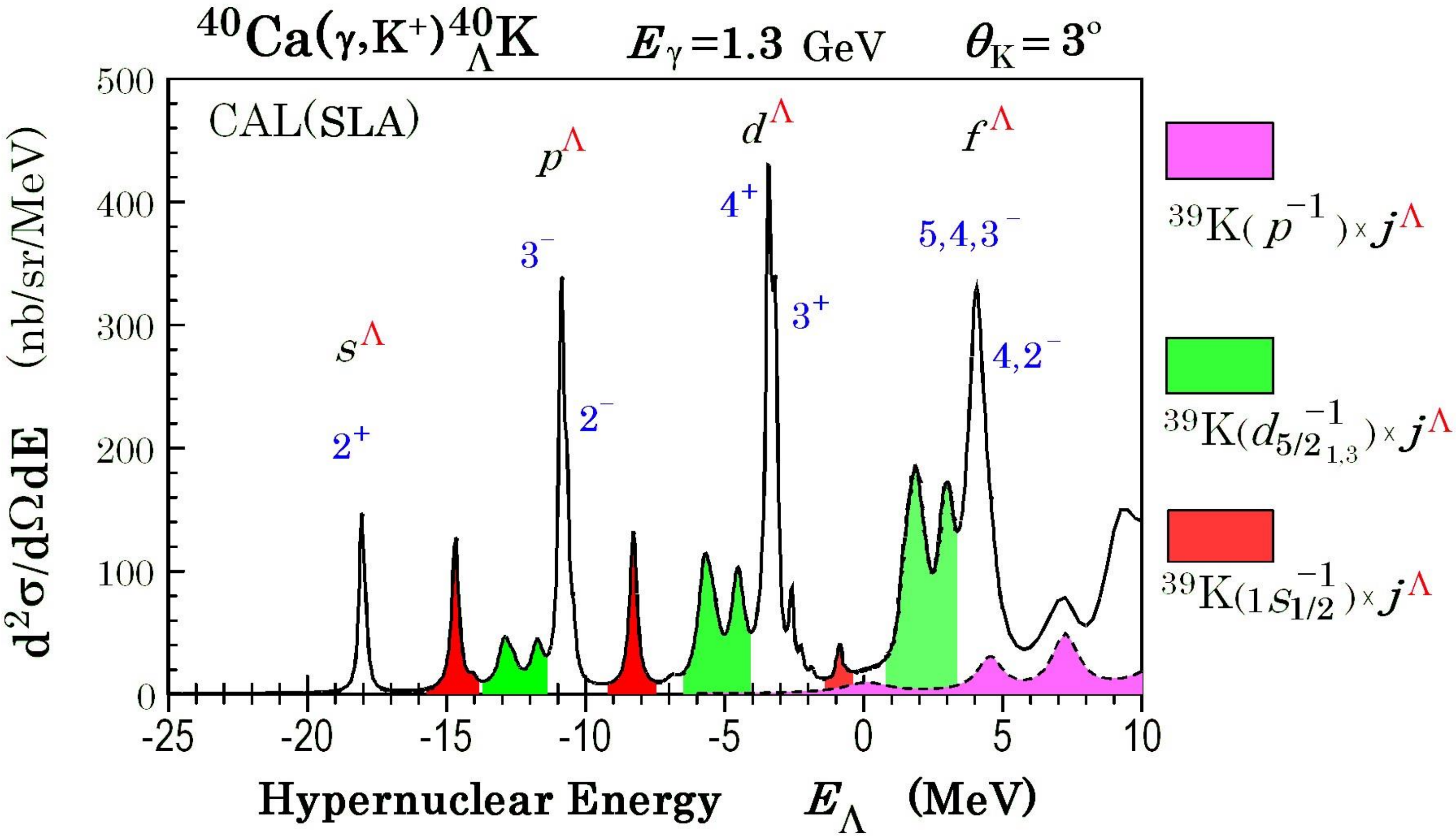
Major peak series : $[{}^{27}Al(5/2^+_1)\times j^\Lambda]_J$ with $j^\Lambda = s, p, d, \ldots$

Exp. data: Fujii et al, Proc. SNP12 workshop (2012)

Seems promising, (waiting for the finalization of analysis)

^{40}Ca (LS-closed shell case):

high-spin states with natural-parity $(2^+,3^-,4^+)$



Major peak series : $[\,^{39}\mathrm{K}(d_{3/2}^{-1};\mathrm{gs})\times j^\Lambda]_J$ with $j^\Lambda = s, p, d, f, \ldots$

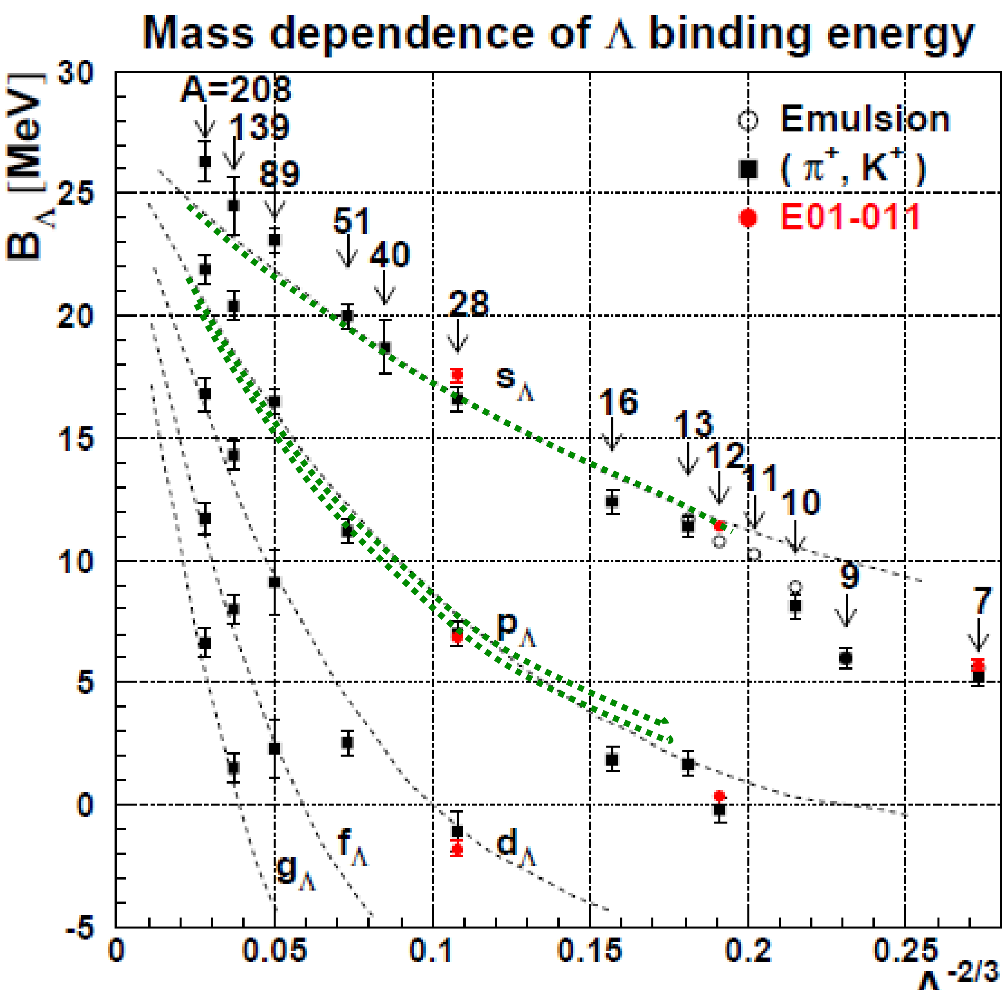
SingleSingle particle energy of Λ

Experimental data

(e,eK+), high resolution (π+,K+)

$E(s_\Lambda, p_\Lambda, d_\Lambda, f_\Lambda, ..)$ < 0.1 MeV accuracy

γ spectroscopy for E1(p_Λ -> s_Λ)



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?

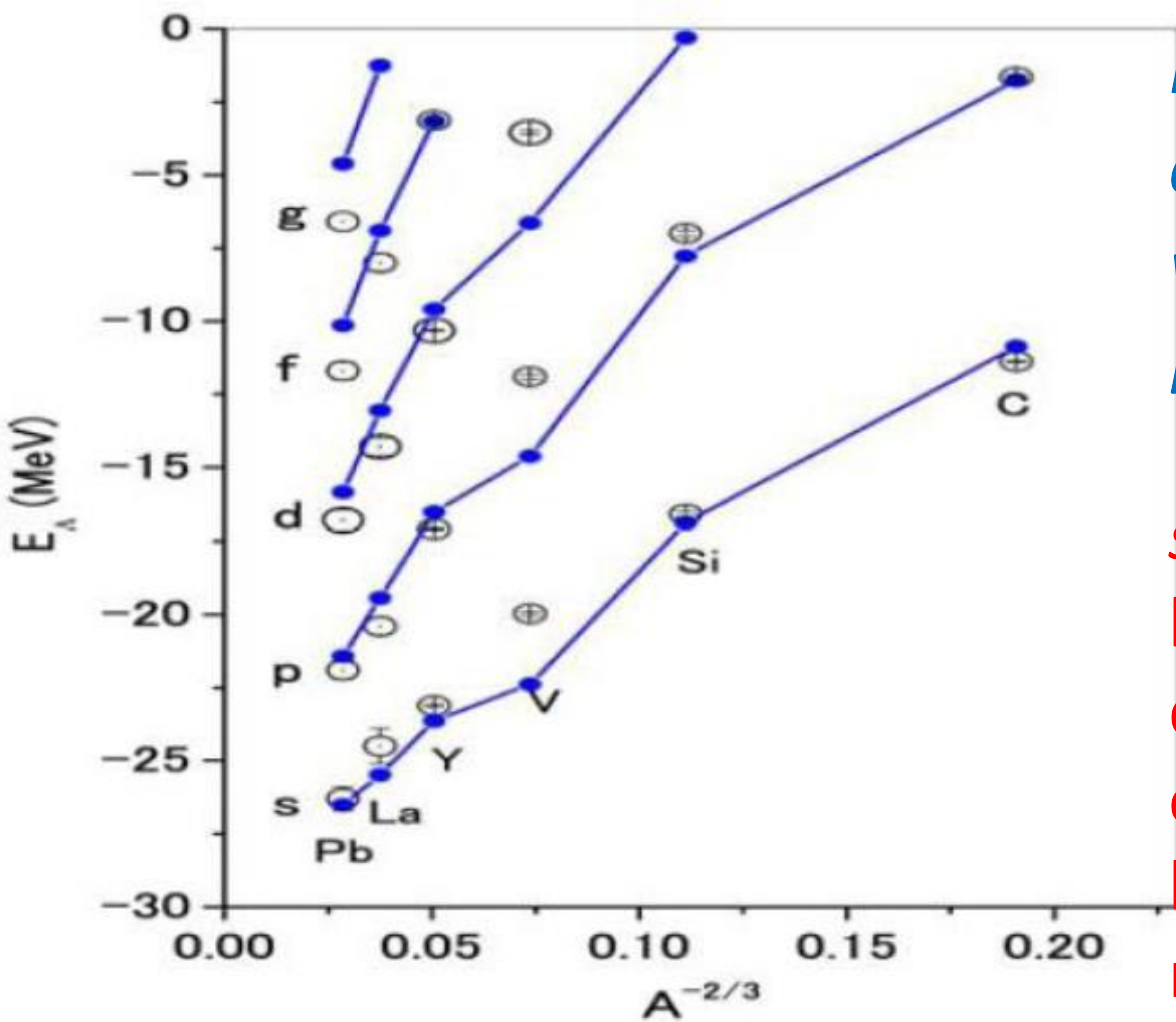
Baryons and bare nuclear forces may change in nucleus)

– theoretical challenge

Theor. Single-particle energies of Λ

G-matrix（ESC08c）results vs. experiments

(Y. Yamamoto et al.: PT. S.185 (2010) 72 and priv. commun.)



High resolution exp. data over wide A are necessary.

sd, *fp*-shell and heavier data are quite Important to extract the Λ behavior in nuclear matter.

4. New aspects observed/expected in strangeness many-body systems

4-1. Shrinkage effects by Λ–addition

Predicted

Motoba et al. 3-cluster model(1983)

Hiyama et al. 3- and 4-cluster model (1998)

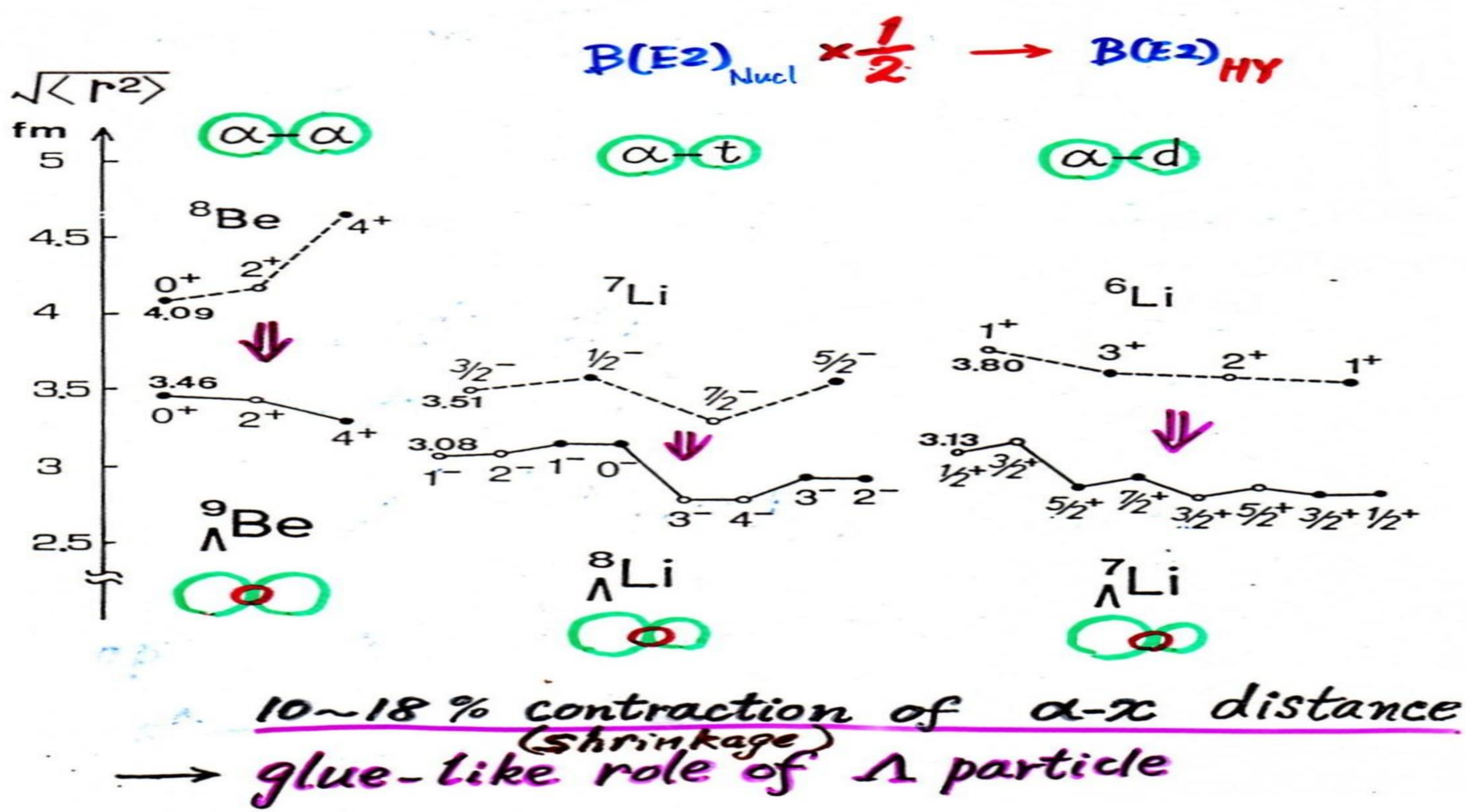
Confirmed

EXP. Tamura et al (1998, 2000,2001)

Shrinkage due to Λ participation

("glue-like role" of Λ)

T. Motoba, H. Bando and K. Ikeda, Prog. Theor.Phys.**70** (1983) predicted by *Microscopic* **α+d+Λ** *model*



Renewed Calculation by E. Hiyama, M. Kamimura, K. Miyazaki, and T. Motoba, Phys. Rev. C59, 2351 (1999),

Microscopic Λ5He＋**p**＋**n** *model*
to see free **p** *and* **n** *dynamics.*

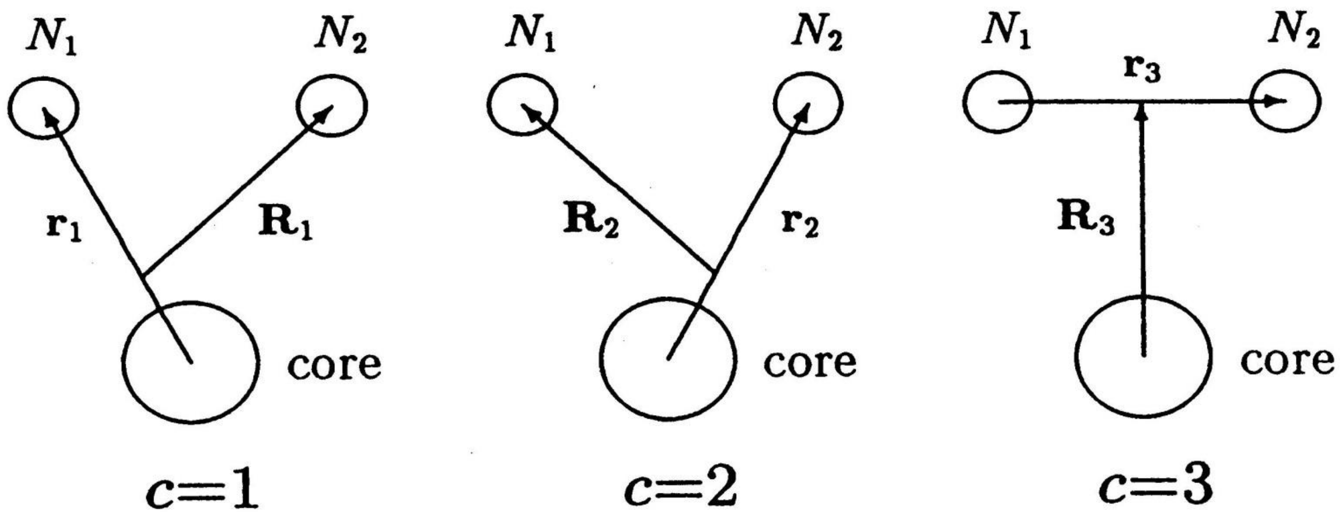
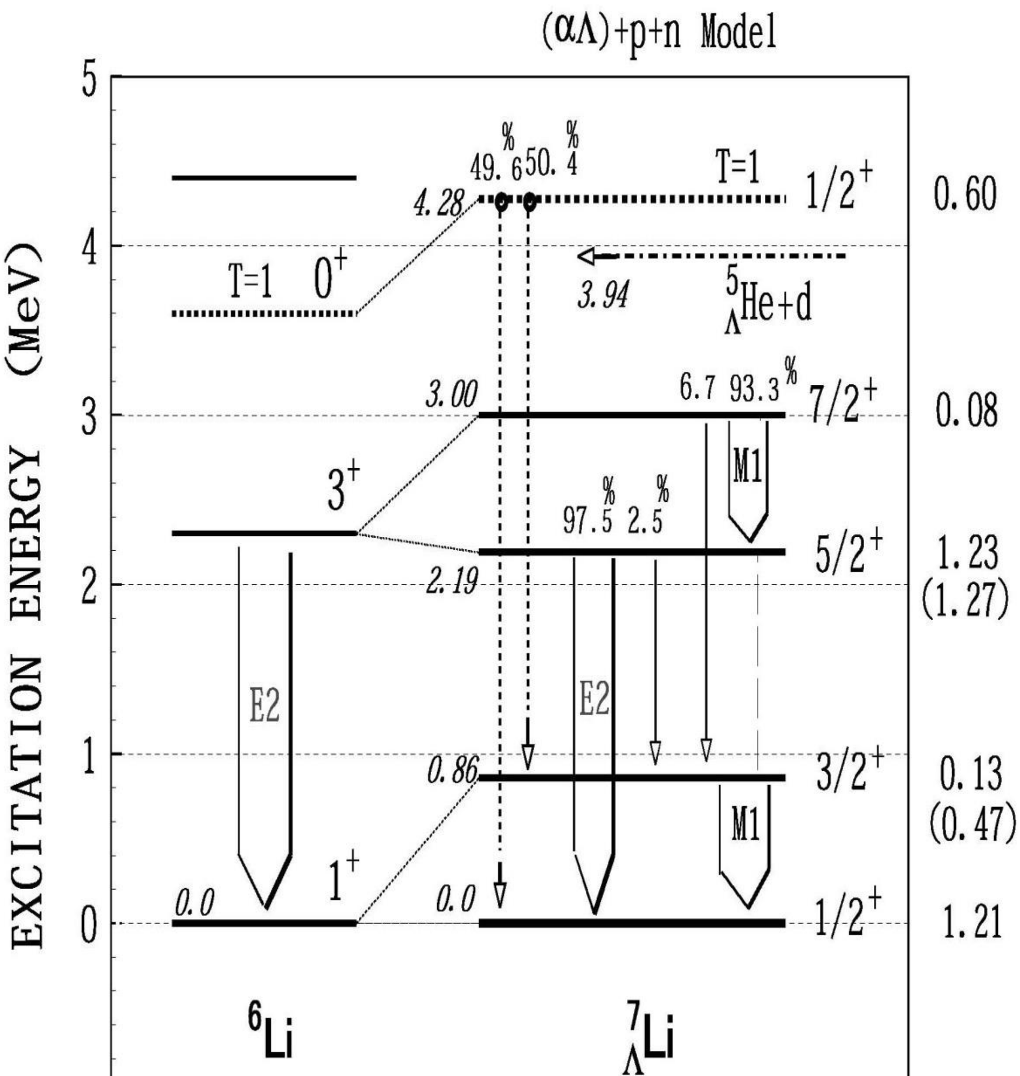
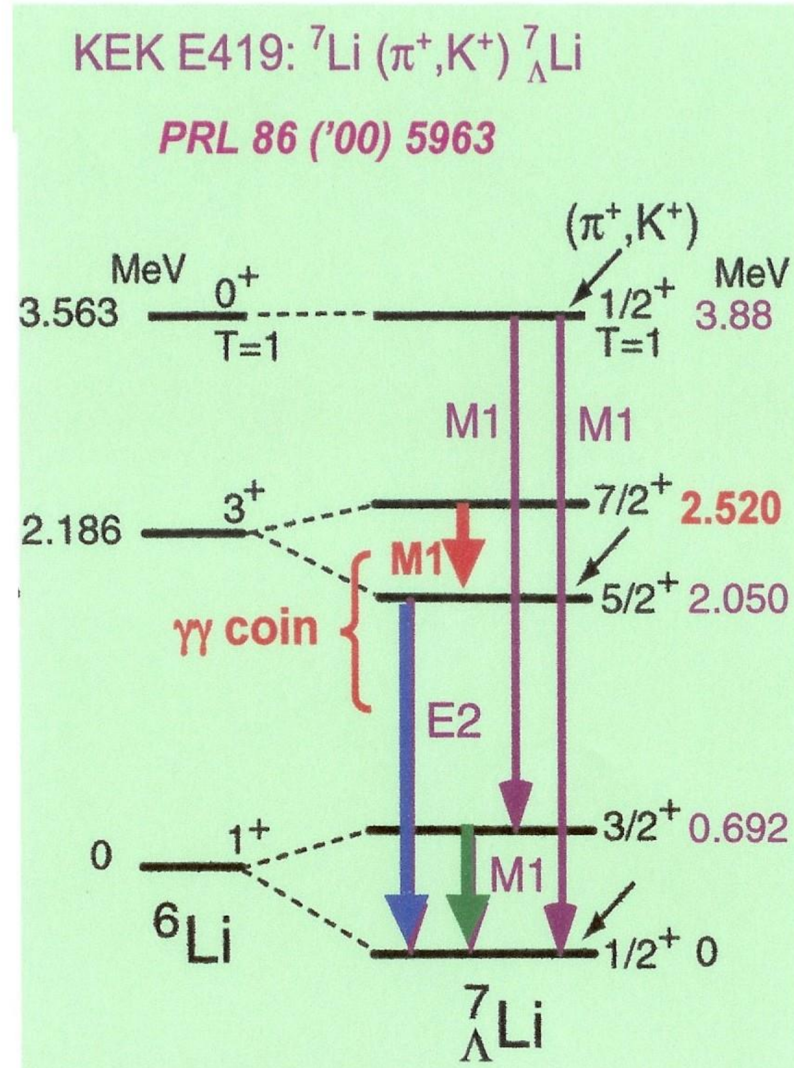


FIG. 3. Jacobian coordinates of the three rearrangement channels of the "core"$+N+N$ model. Here, "core" is α for the $A=6$ nuclei and ${}^{5}_{\Lambda}$He for the $A=7$ hypernuclei.

B(6Li,E2:3+→1+) vs. B(Λ7Li,E2;5/2+→1/2+)





All the bound states determined

Contraction of R_{core}-(pn) without changing p-n distribution (Hiyama et al, 1998)

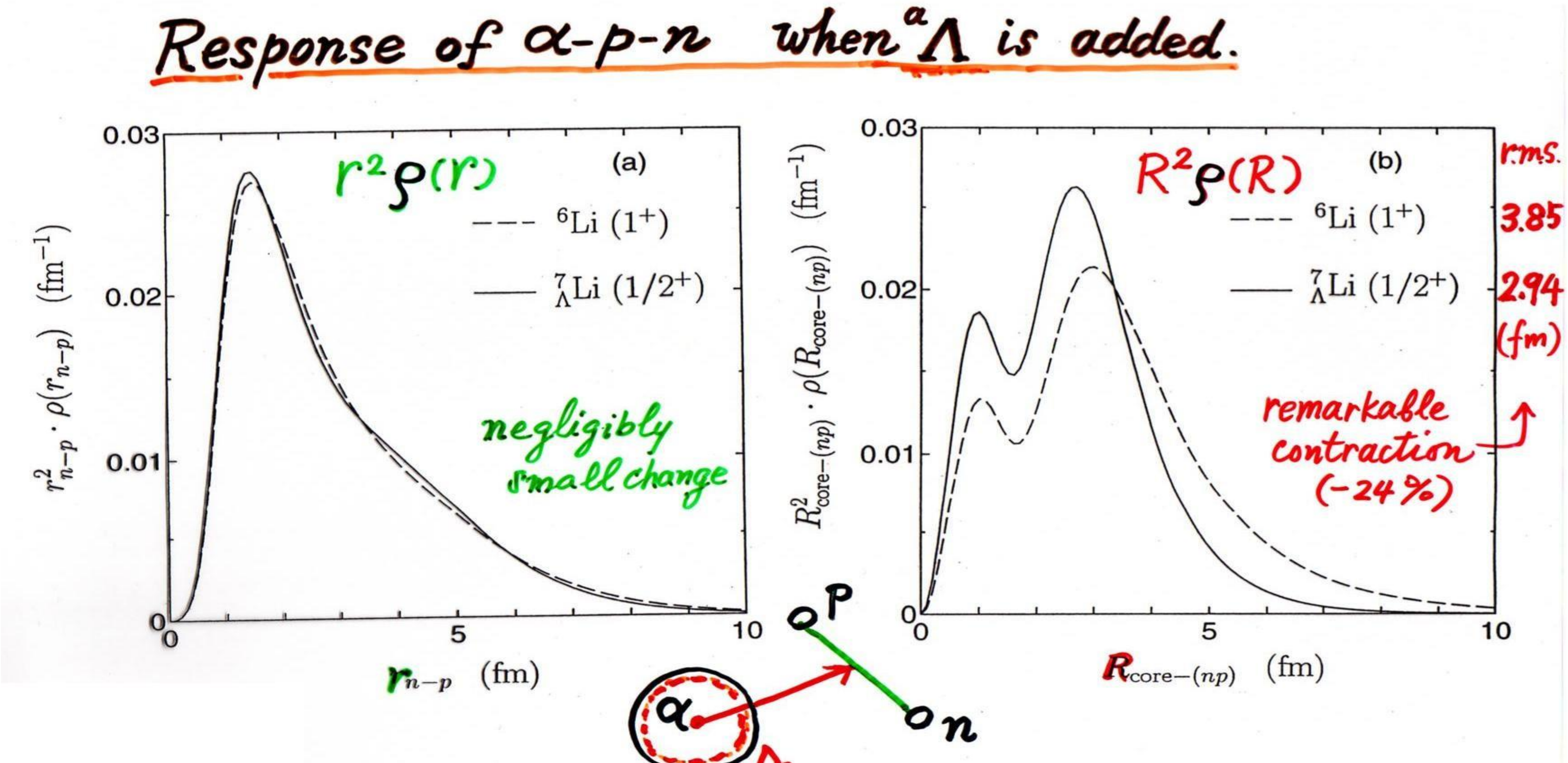


Fig. 4. (a) The $n-p$ relative density distribution $\rho(r_{n-p})$ defined by Eq.(4.6) multiplied by r^2_{n-p}. (b) The (np) pair c.m. density distribution $\rho(R_{\mathrm{core}-(np)})$ defined by Eq.(4.7) multiplied by $R^2_{\mathrm{core}-(np)}$. Both are for the ground states of ^{6}Li and $^7_\Lambda$Li.

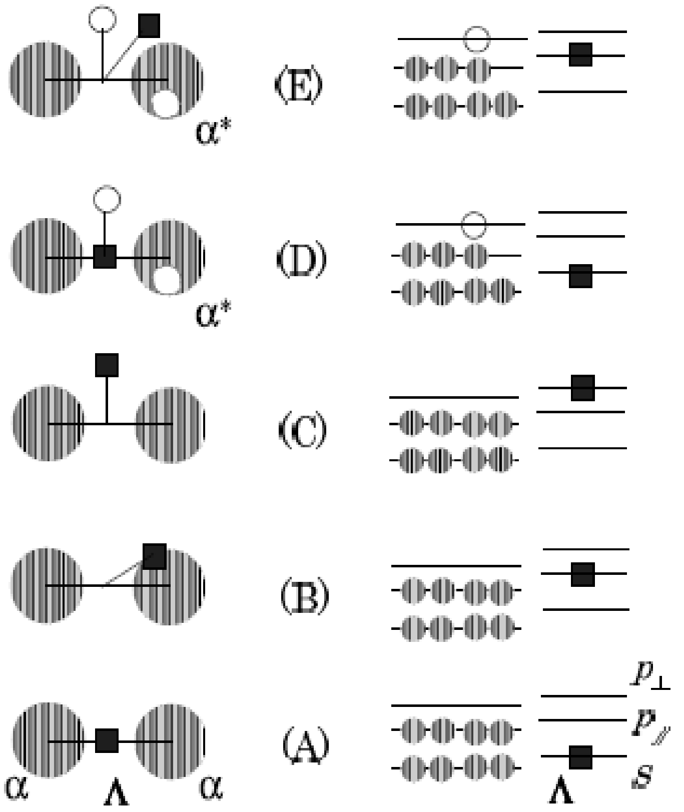
$$\rho(R) = \int |\Psi|^2 d\mathbf{r} d\hat{\mathbf{R}} / 4\pi$$

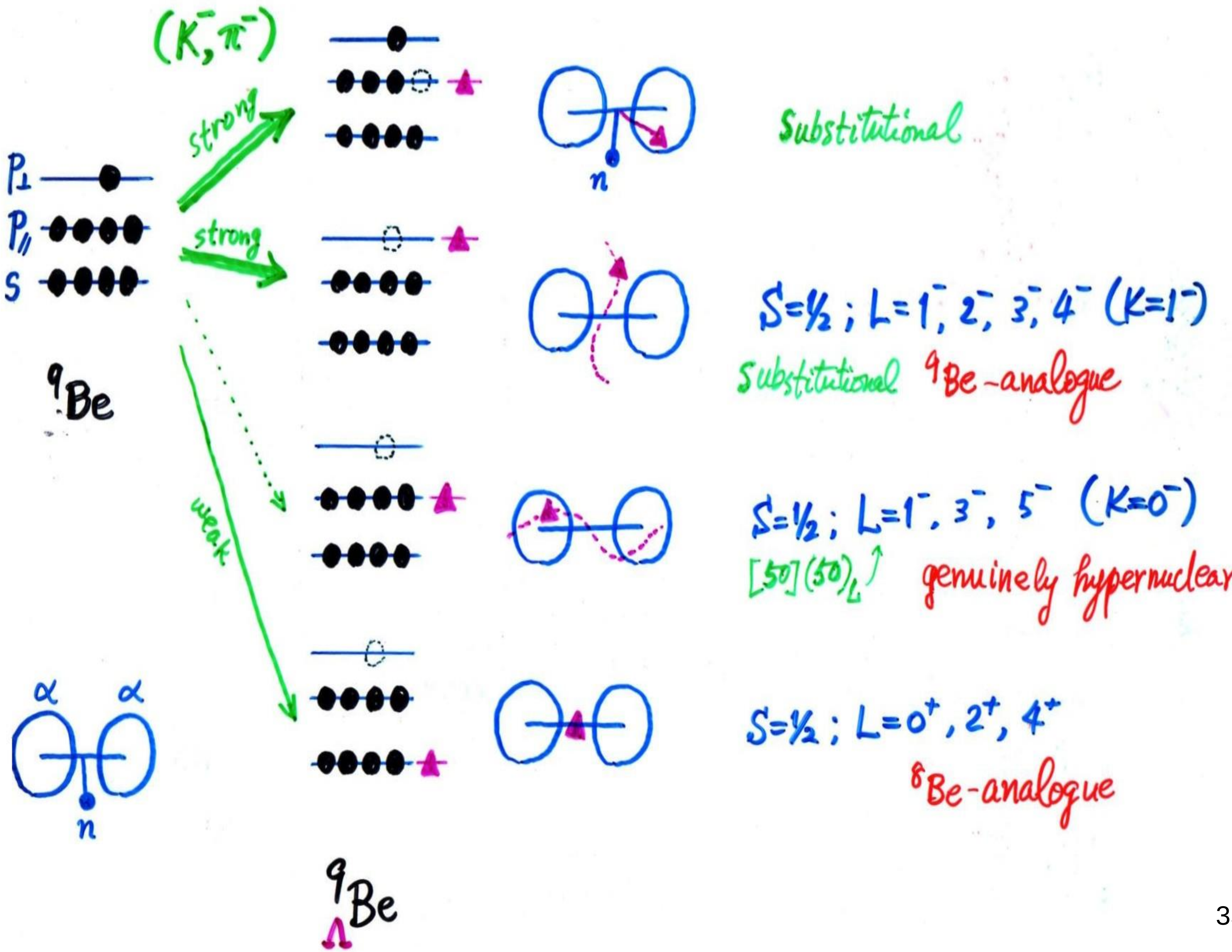
Shrinkage: glue-like role of Λ *confirmed*

B(E2) in e^2fm^4	Dalitz -Gal Shell M. (1978)	Motoba et al. 3-Cluster (1983)	Hiyama et al. 3-Cluster (1998)	EXP. Tamura et al (1998, 2000,2001)
B(M1:3/2+→1/2+)	0.364	0.352	0.322	-
B(E2:5/2+ →1/2+) *eff.chrg: δe=0.15e	8.6	2.46 (4.16*)	2.42 (4.09*)	4.1+-1.1
B(E2:5/2+ →3/2+)	3.1	0.40	0.74	
B(E2:5/2+→all)/**B(E2)**c	**1.0** assumed	0.44	0.33	
Γ_B		0.49	0.32	
$R_{cd}(^7Li)/R_{\alpha d}(^6Li)$		0.83	0.75	0.87
Lifetime(5/2+) ps		6.56	6.67	5.2+-1.4

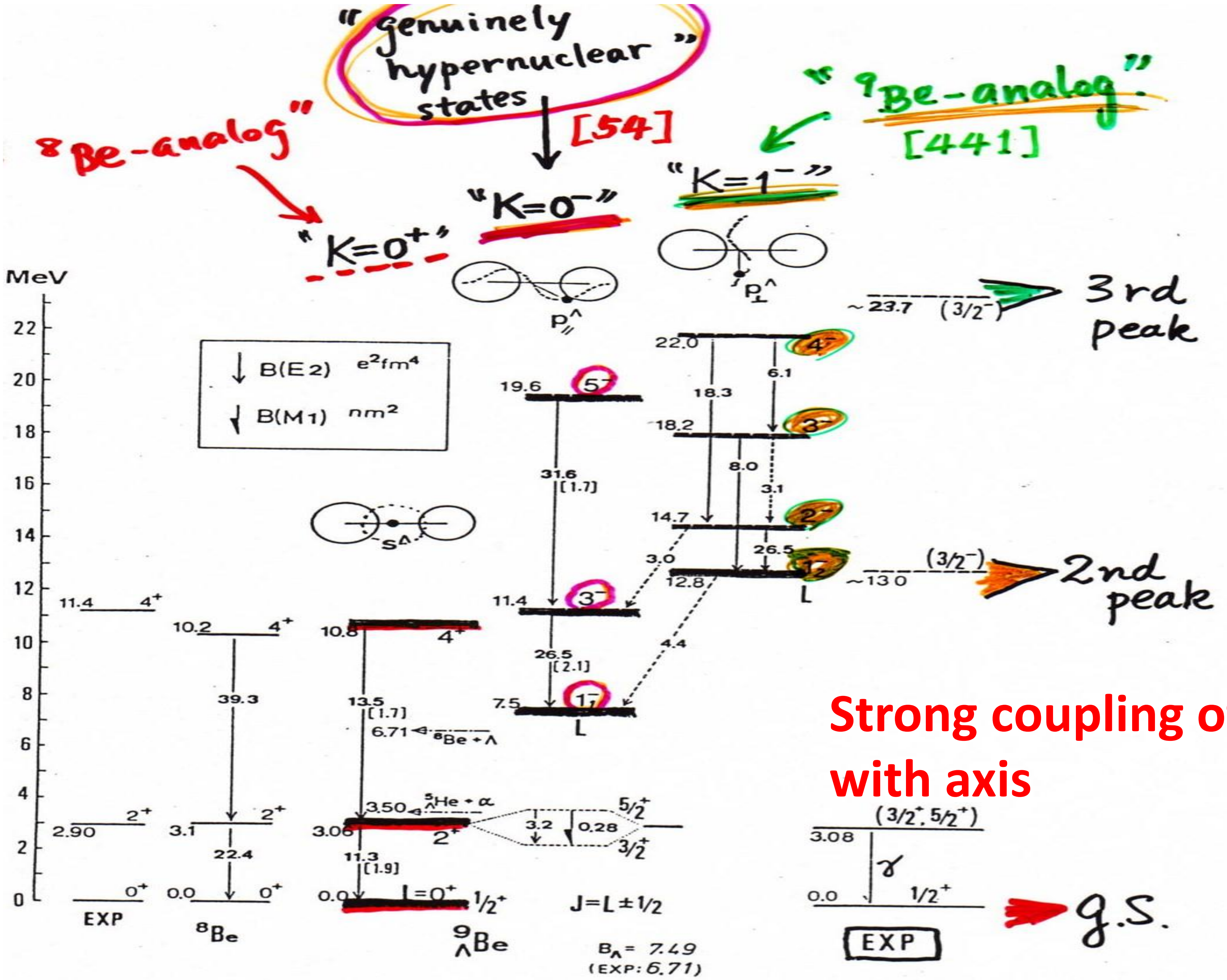
4. New aspects observed/expected in strangeness many-body systems

4-2. Appearance of genuinely hypernuclear states



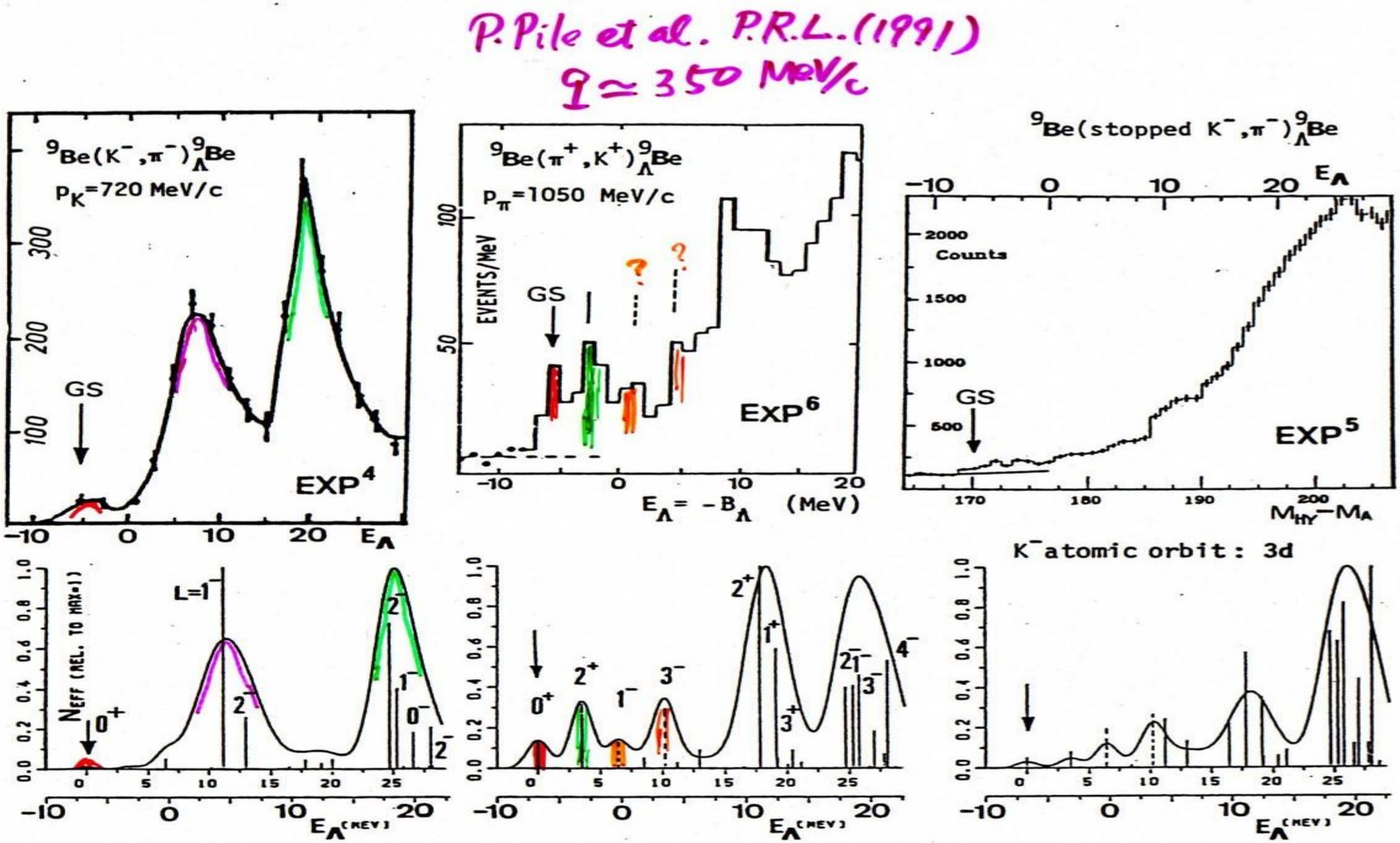


(K⁻, π⁻)
strong
strong
weak
P⊥
P∥
S
⁹Be
α
α
n
n
Substitutional
S=½ ; L=1⁻, 2⁻, 3⁻, 4⁻ (K=1⁻)
Substitutional ⁹Be-analogue
S=½ ; L=1⁻, 3⁻, 5⁻ (K=0⁻)
[50](50)_L
genuinely hypernuclear
S=½ ; L=0⁺, 2⁺, 4⁺
⁸Be-analogue
⁹_ΛBe



Strong coupling of Λ with axis

All the existing exp.data can be explained.



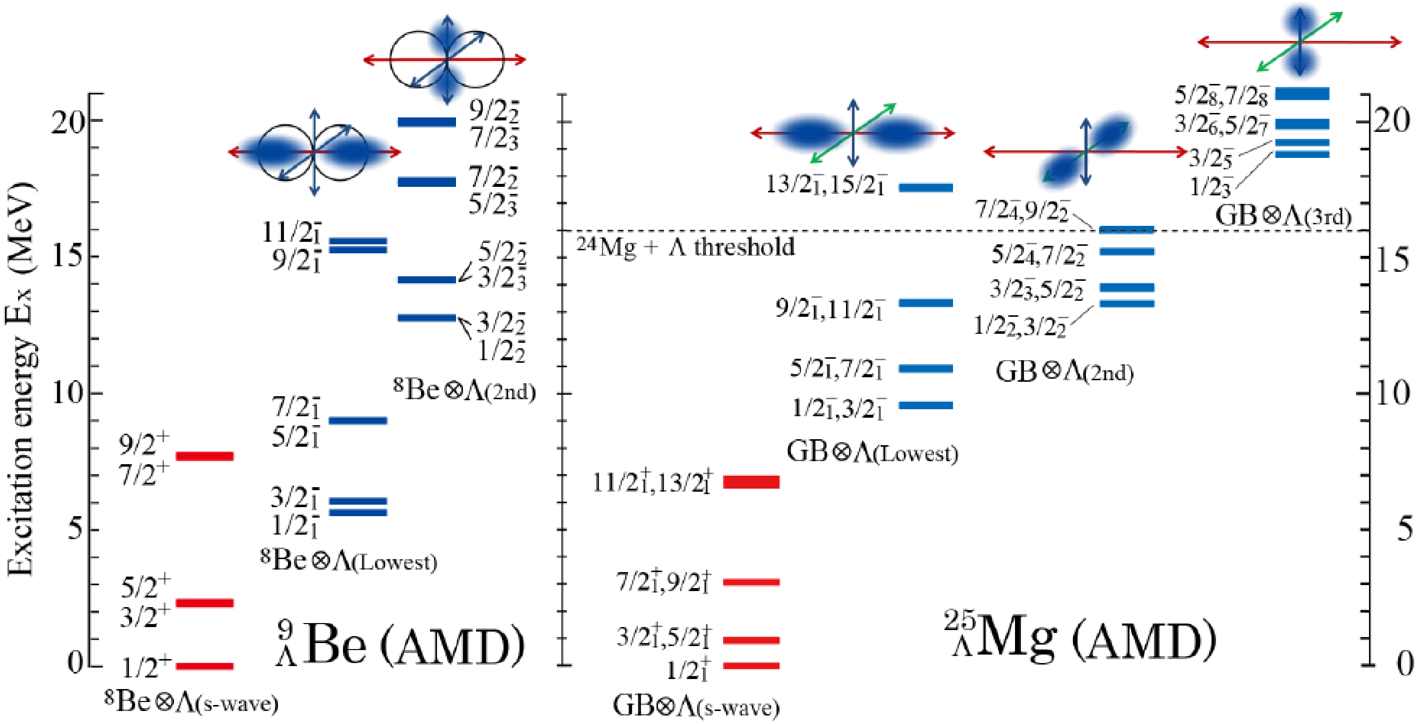
CAL: T. Motoba, H. Bandō, K. Ikeda : PTP (1983)
T. Yamada et al., P.R. C38 (1988)

This concept is extended to sd-shell

Coupling of Λ hyperon with triaxial rotational motions in ^{24}Mg **(Isaka et al, PRC87(2013)**)

Results: Excitation spectra

- **3 bands are obtained by Λ hyperon in *p*-orbit** → **Splitting of the *p* states**
  - ^{24}Mg⊗Λp(lowest), ^{24}Mg⊗Λp(2nd lowest), ^{24}Mg⊗Λp(3rd lowest)



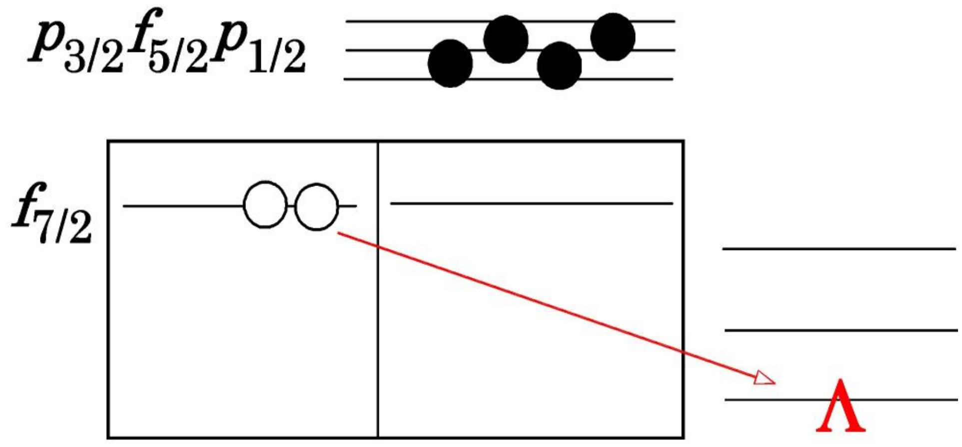
Lowest threshold $^{21}_{\Lambda}$Ne + Λ: in between 8.3 and 12.5 MeV

4. New aspects observed/expected in strangeness many-body systems

4-3. Coupling of Λ with nuclear collective motions such as rotation

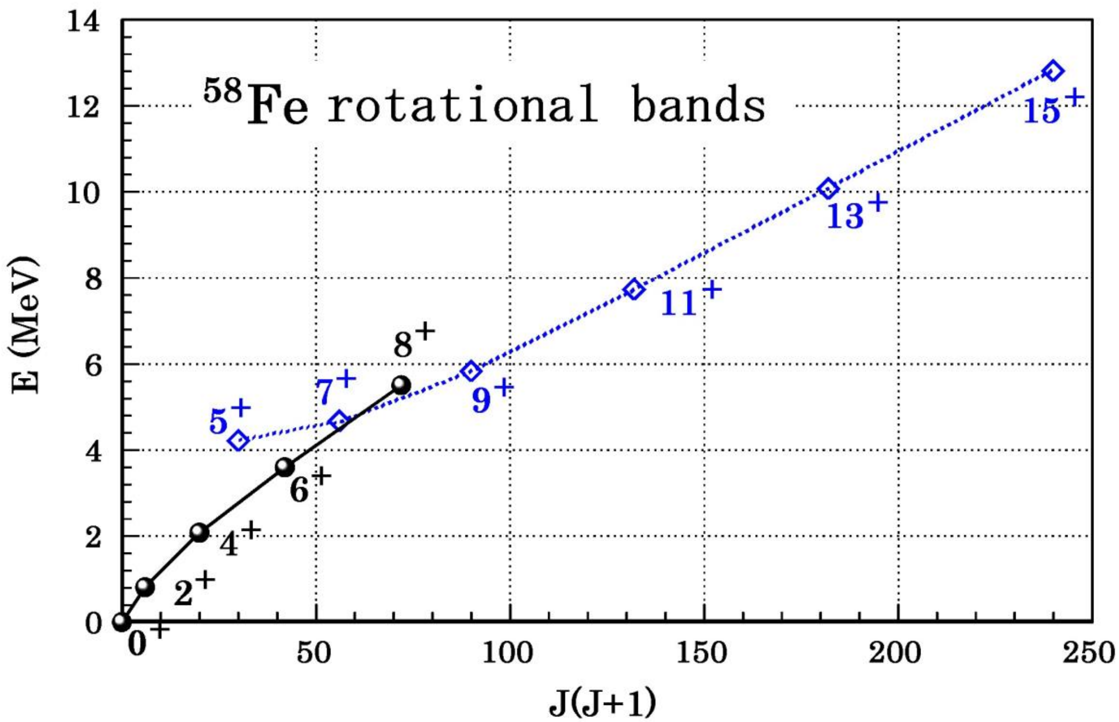
As a promising candidate to observe it in the *fp*-shell region, we propose to use $^{59}Co(\gamma, K^{+})\ ^{59}_{\Lambda}Fe$

$^{59}\mathrm{Co}\ (\gamma, K^{+})\ ^{59}_{\Lambda}\mathrm{Fe}$



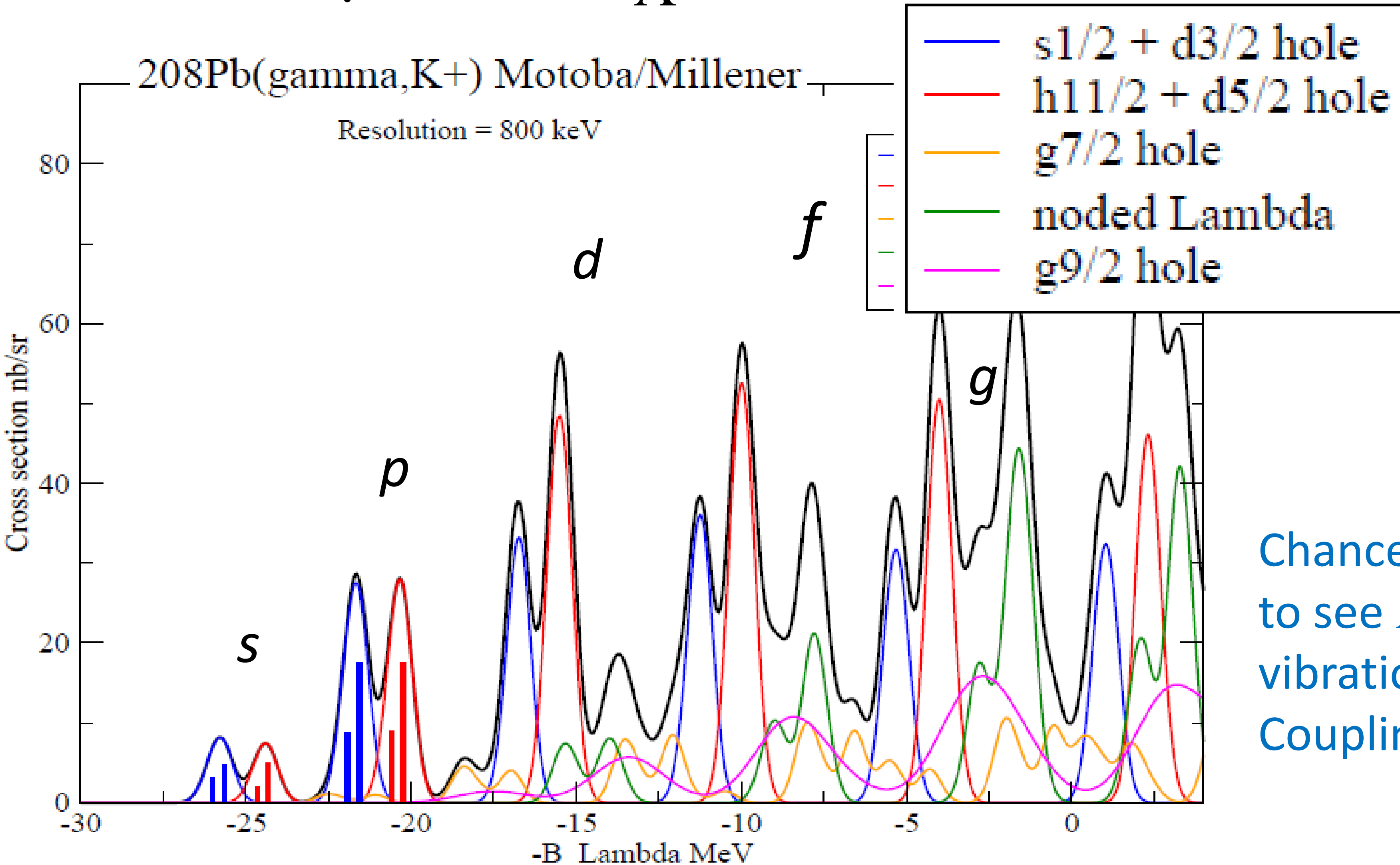
$^{58}\mathrm{Fe}_{32} + \Lambda$

(just preparing CAL)



Interesting to see dynamical coupling of a hyperon with rotation without Disturbance due to the Pauli principle

$^{208}Pb(\gamma,K+)\ ^{208}{}_{\Lambda}Tl$



Chance to see Λ–vibration Coupling?

We have an opportunity to observe a series of Λ orbits ?

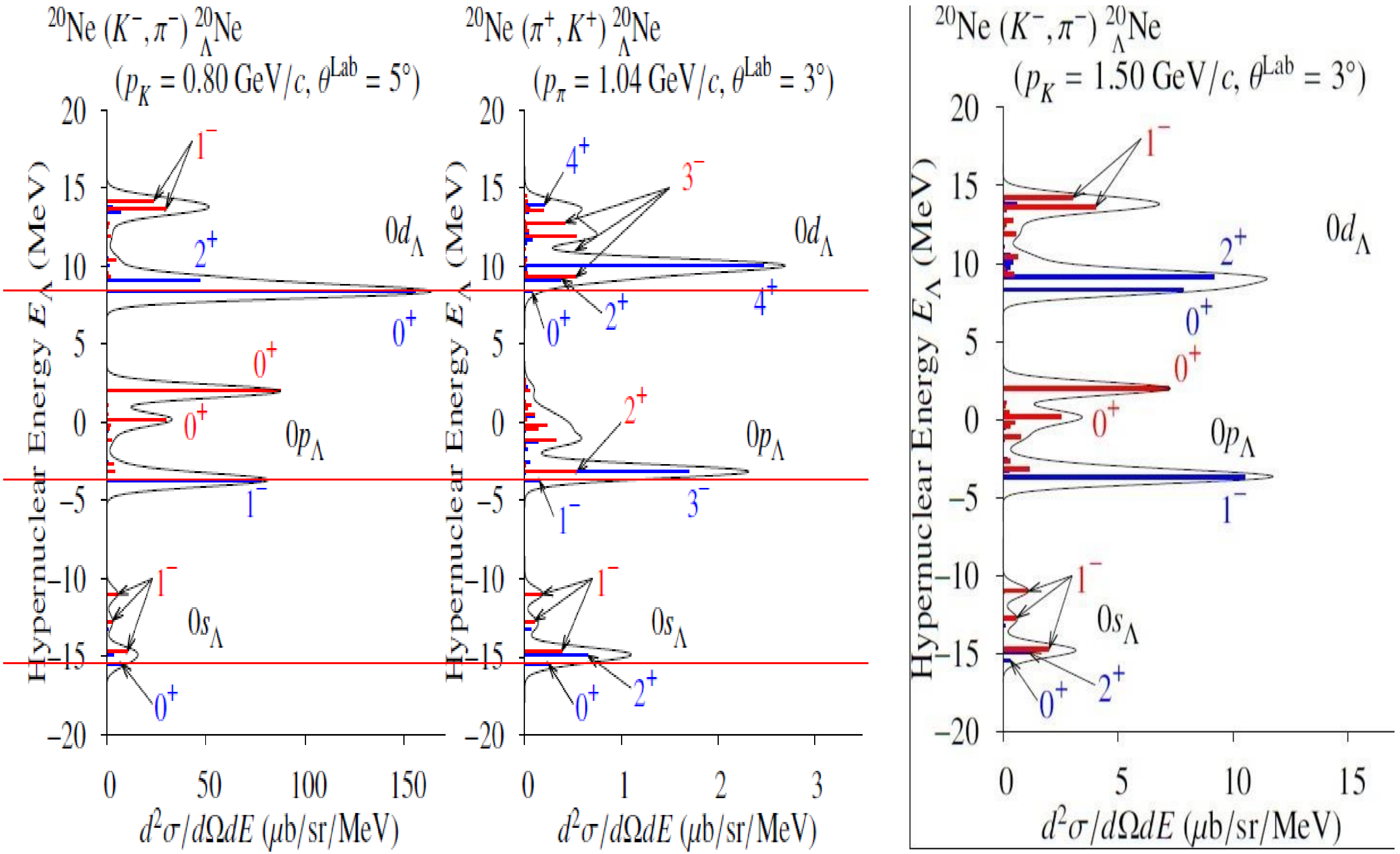
5. Emphasize to compare different production proceses by making use of the J-PARC Kaon beam.

Hypernuclear states will be clarified by:

(1) Compare different kinematics and angular distributions

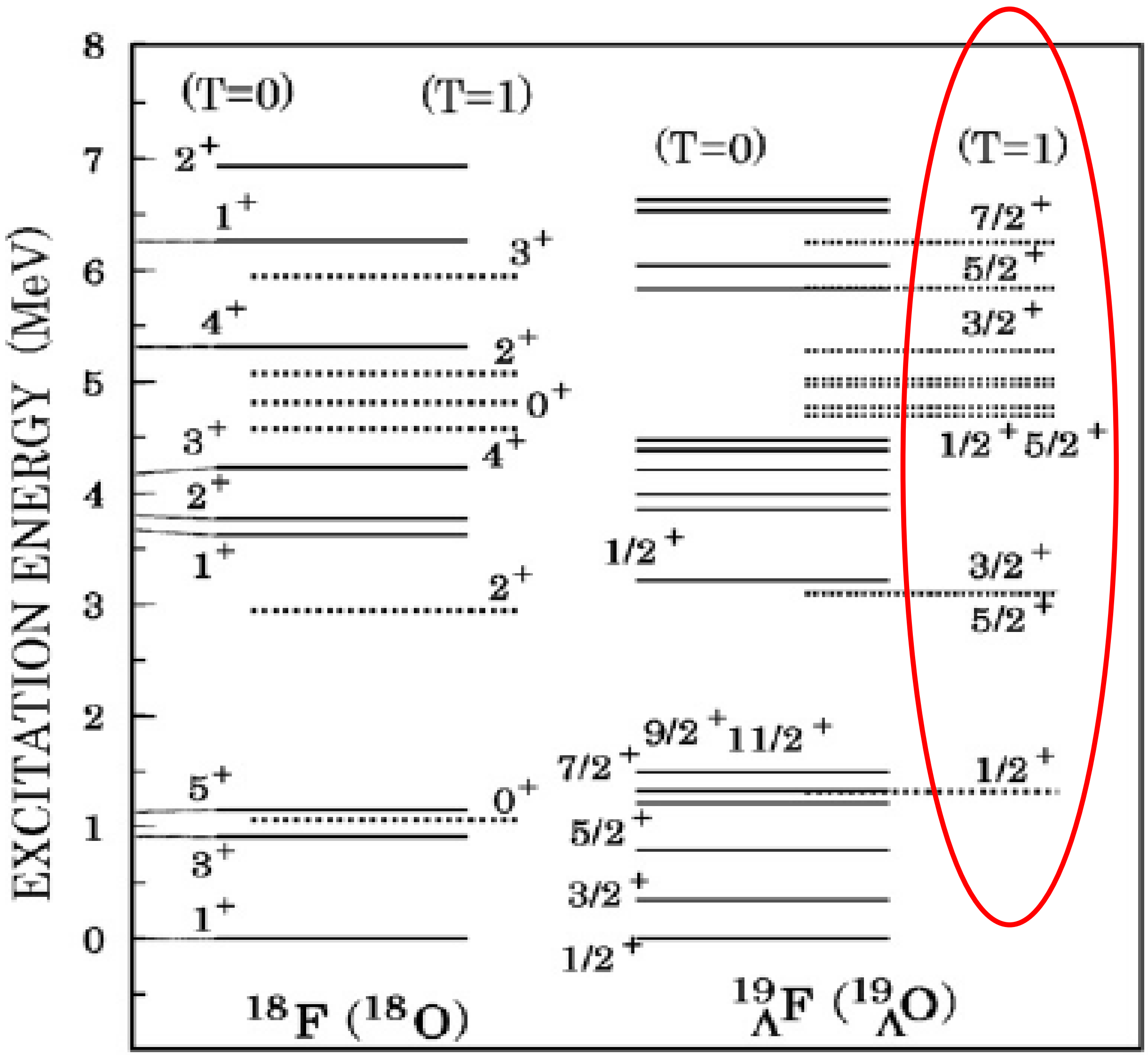
(2) (K-,π-γ) coincidence measurement

Comparison of 3 theor. spectra



And more predictions for the J-PARC projects in

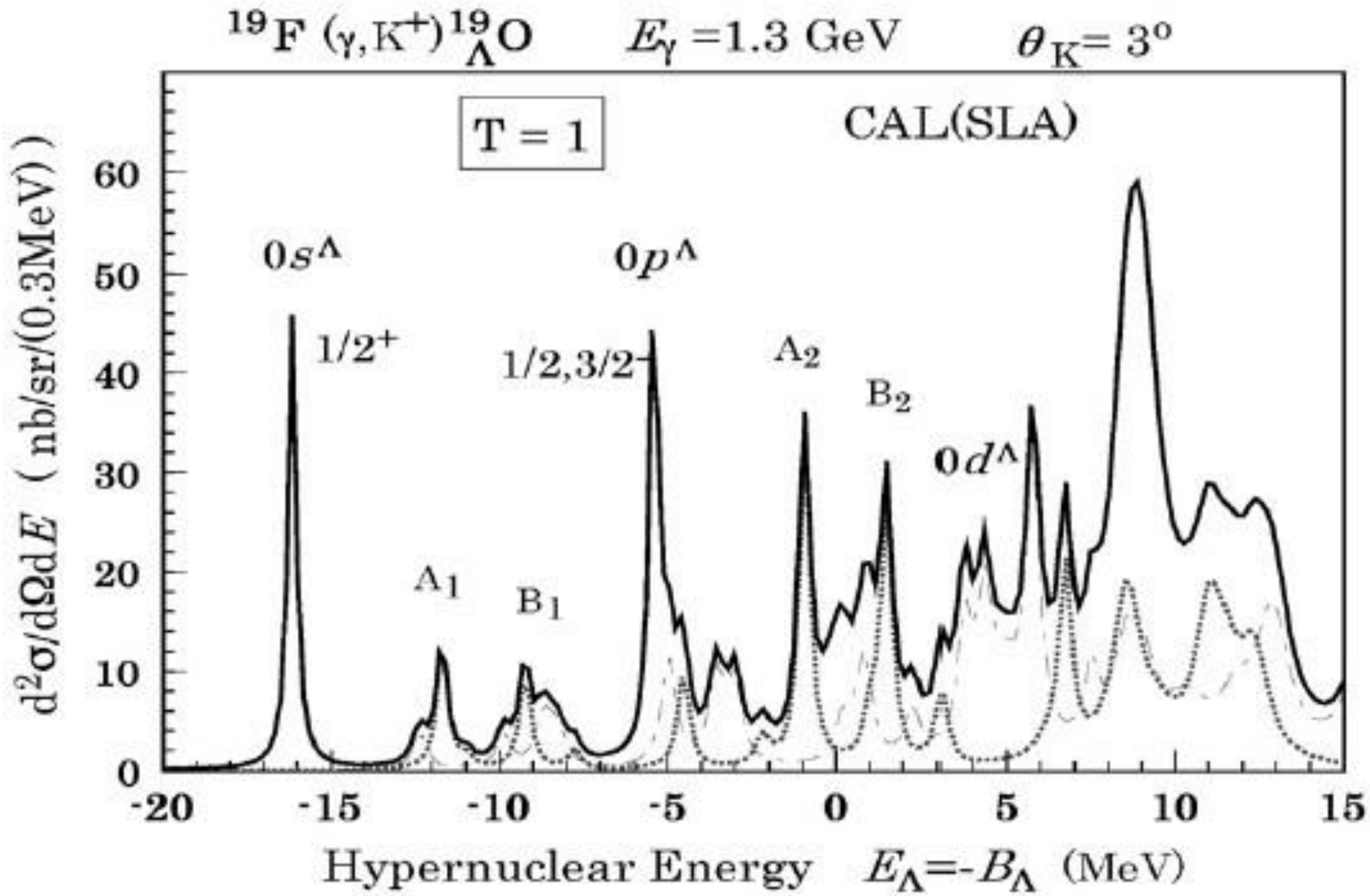
$^{18}F(^{18}O)$ and $^{19}{}_{\Lambda}F$ $(^{19}{}_{\Lambda}O)$ Energy levels



T=1 states are excited in (γ,K+)

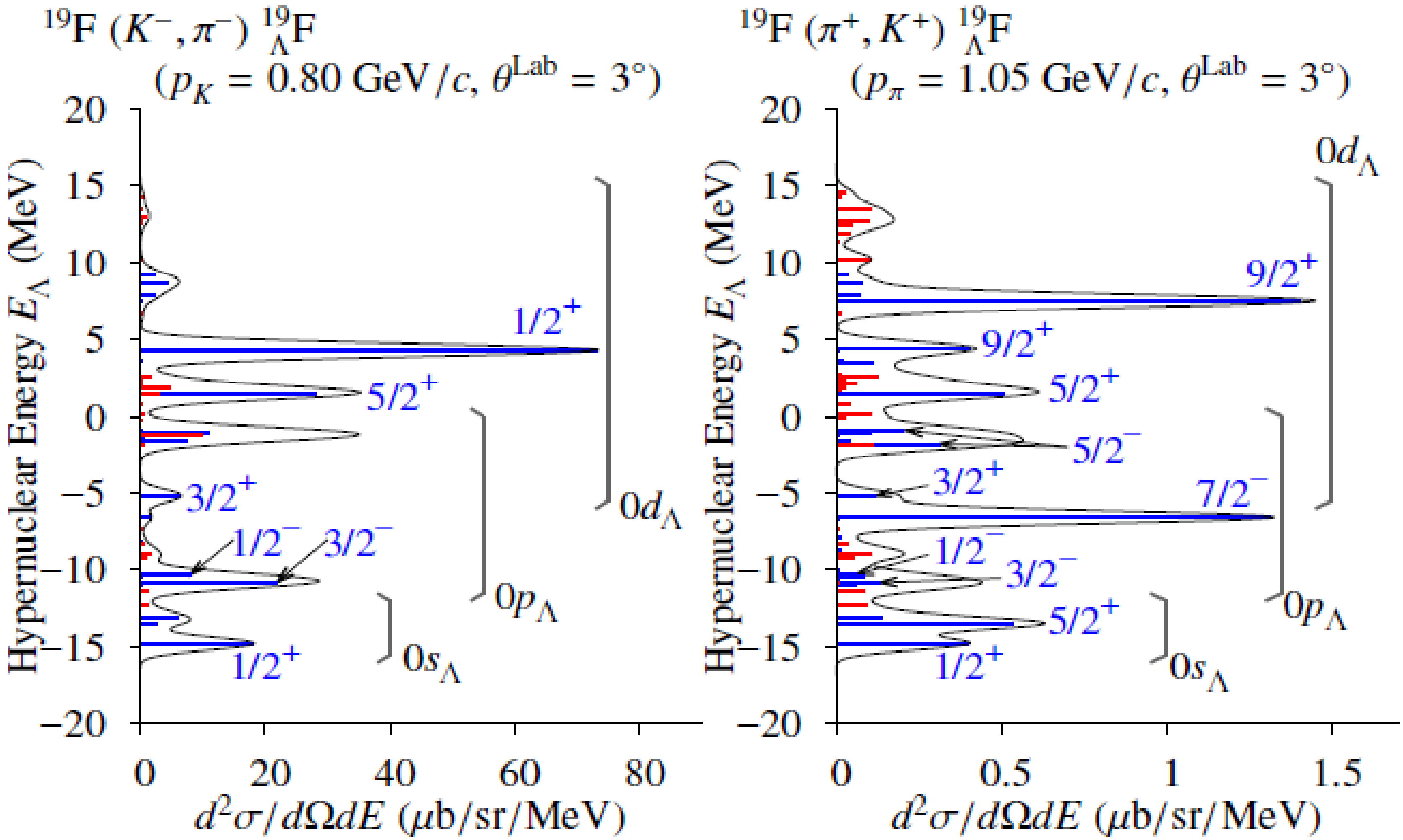
Lightest sd-shell target: ^{19}F

A's: $p_{1/2}$-hole series, B's: $p_{3/2}$-hole series



Umeya's Calculation

Results: Production cross sections of $^{19}F(K^-,\pi^-)$ and $^{19}F(\pi^+,K^+)$



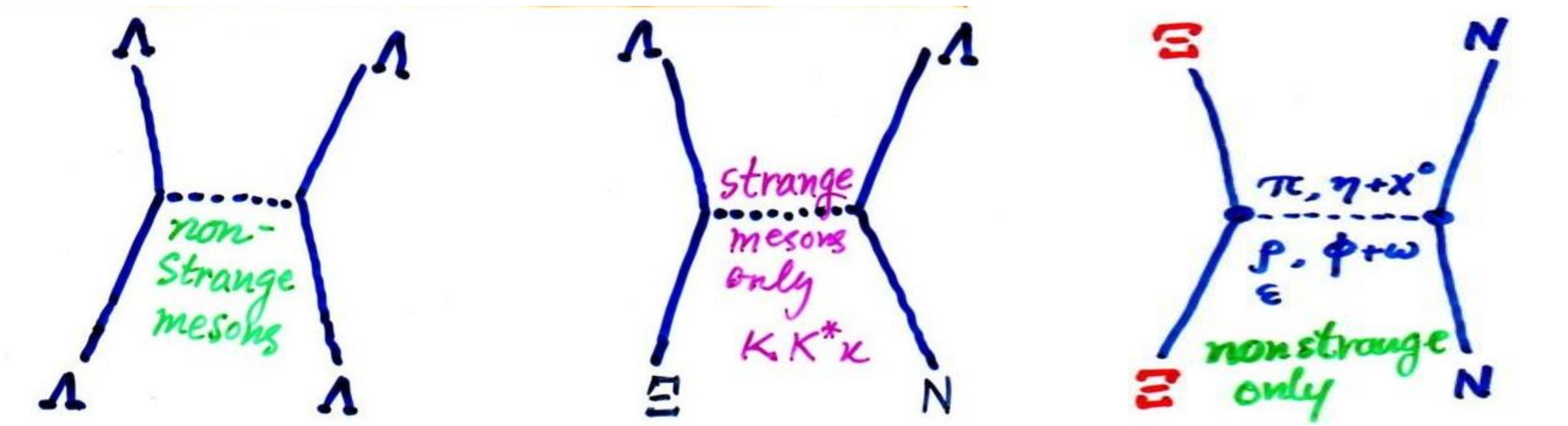
6. Ξ-hypernuclei and double-Λ hypernuclei vs. S=-2 interactions

> **One of the most interesting subjects at J-PARC Is to get a reliable answer on the existence of Ξ-hypernuclei, providing an important restriction on Ξ-N interaction.**

> **Another subject is to produce many double-Λ hypernuclei**

Why Ξ-hypernuclei ?

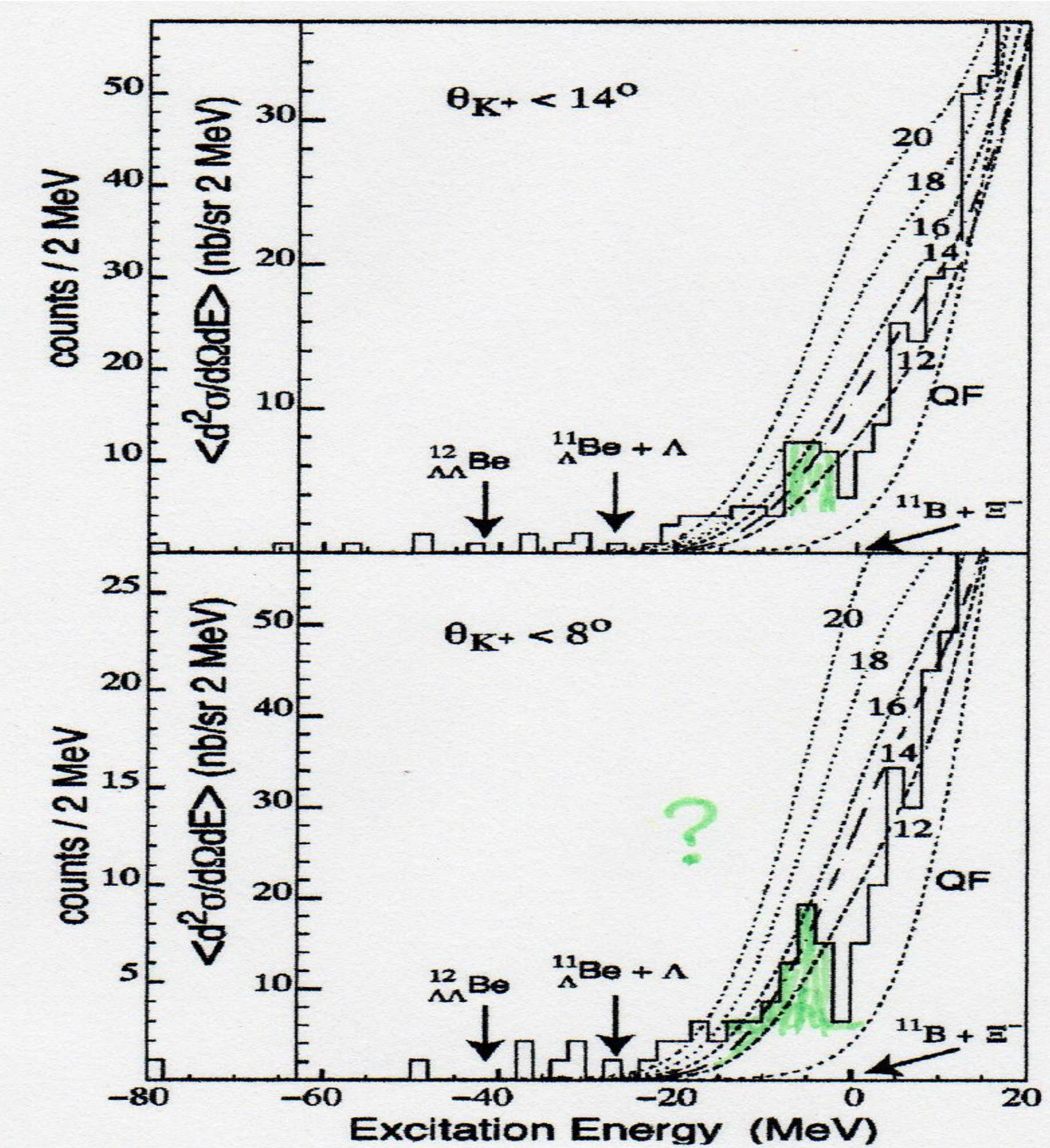
1) They provide unique information on the *S*=-2 B-B interactions inaccessible otherwise.



2) High-priority experiment at J-PARC（2009－

E-05: "Spectroscopic study of Ξ-hypernucleus via the ^{12}C(K-,K+) $_{\Xi}{}^{12}$Be reaction" by T. Nagae et al.

→ Realistic Calculations are required.



BNL-E885

P. Khaustov et al, PRC 61 (2000)

BS strengths observed,but **peaks not confirmed.**

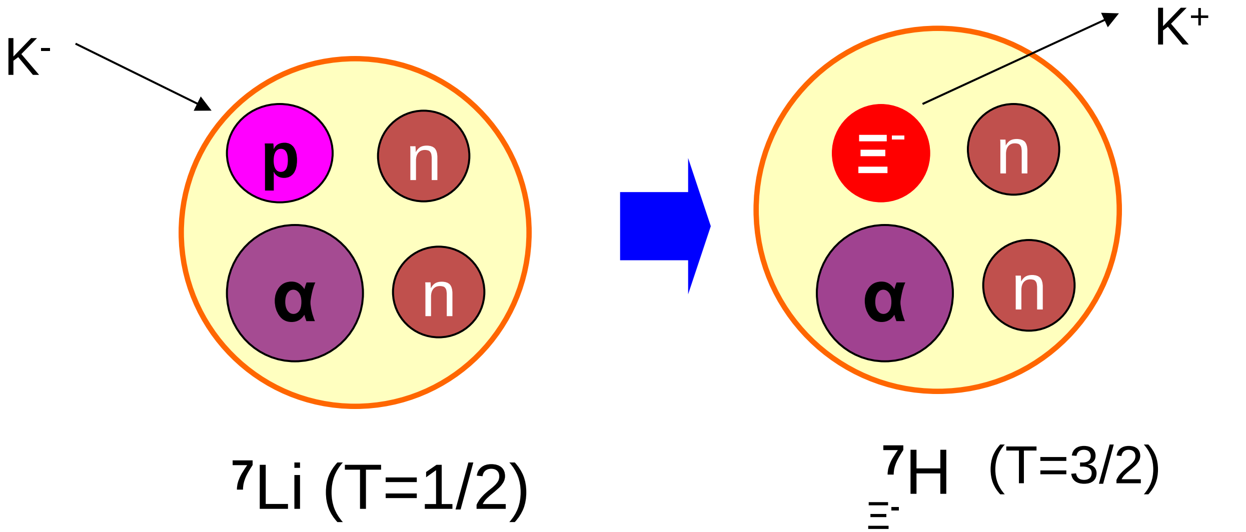
Suggesting:

only WS-pot. depth:

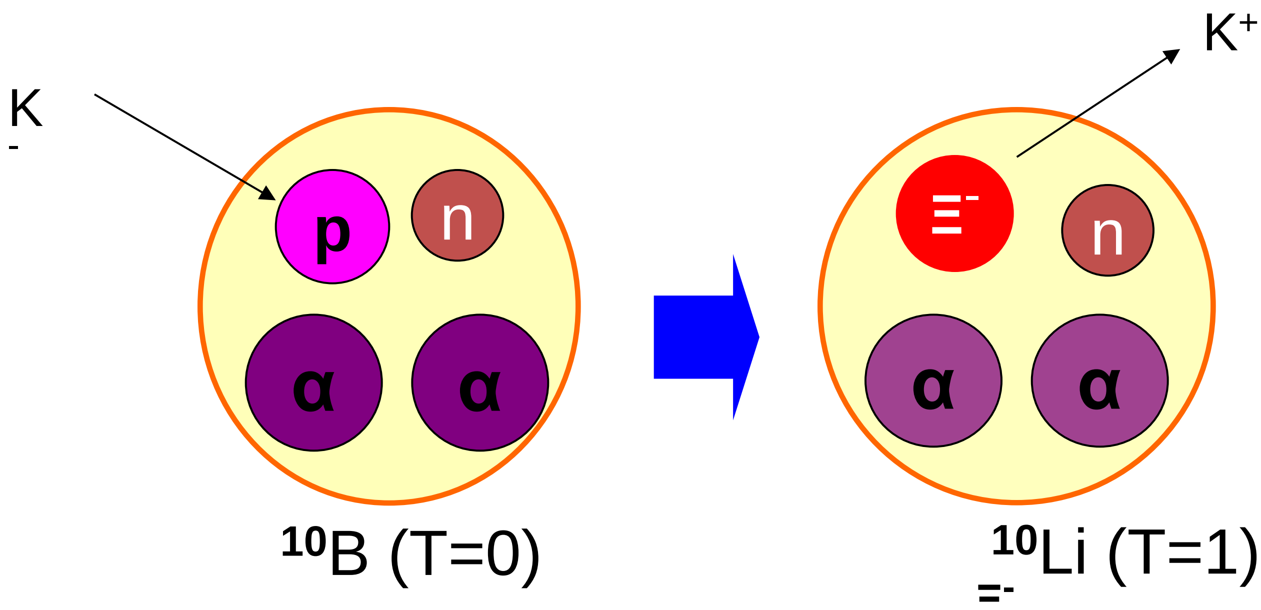
U=12-14 MeV or less.

"shallow"

As the second best candidates to extract information about the spin-, isospin-independent term V_0, we propose to perform…



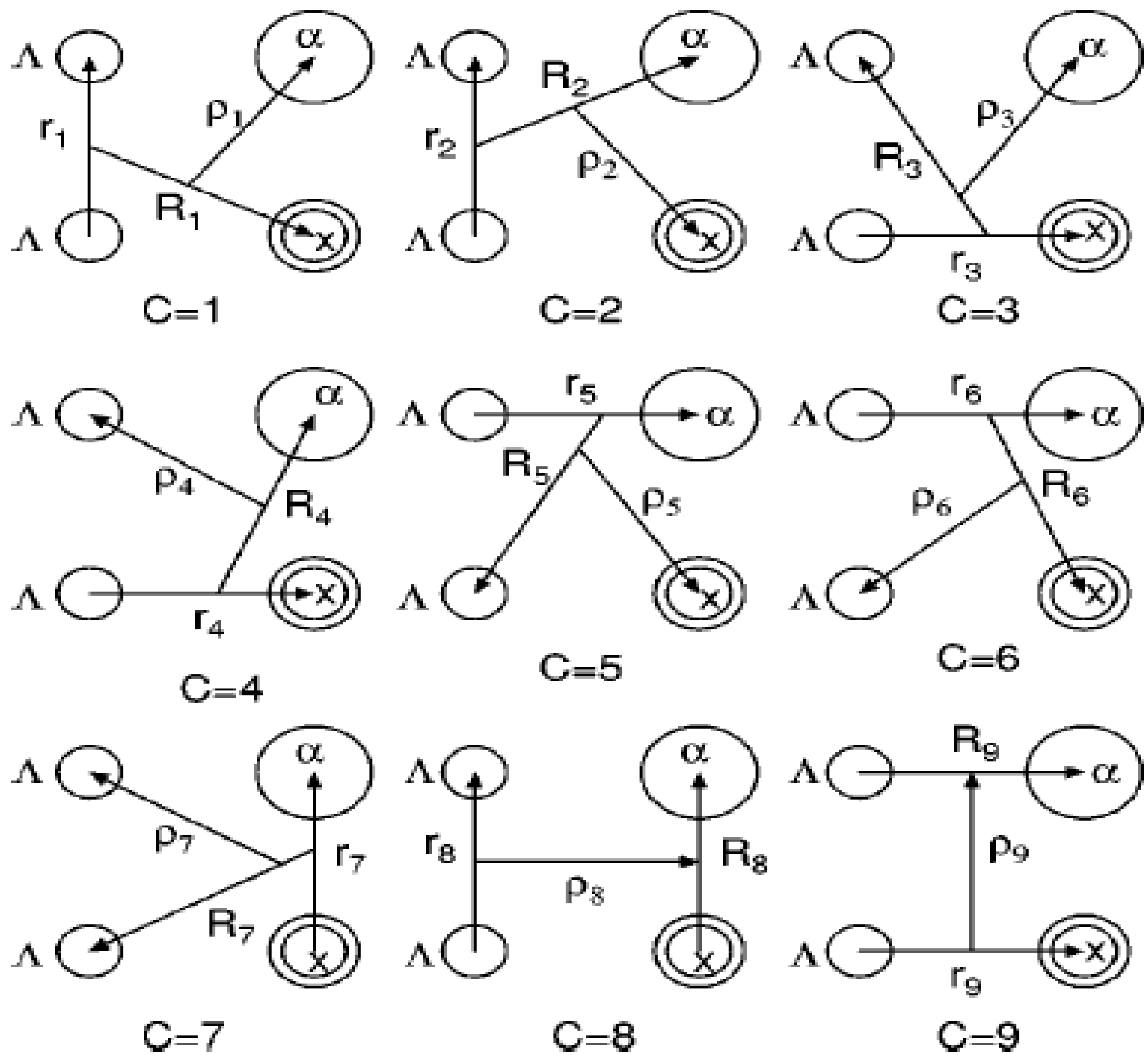
Why they are suited for investigating V_0?



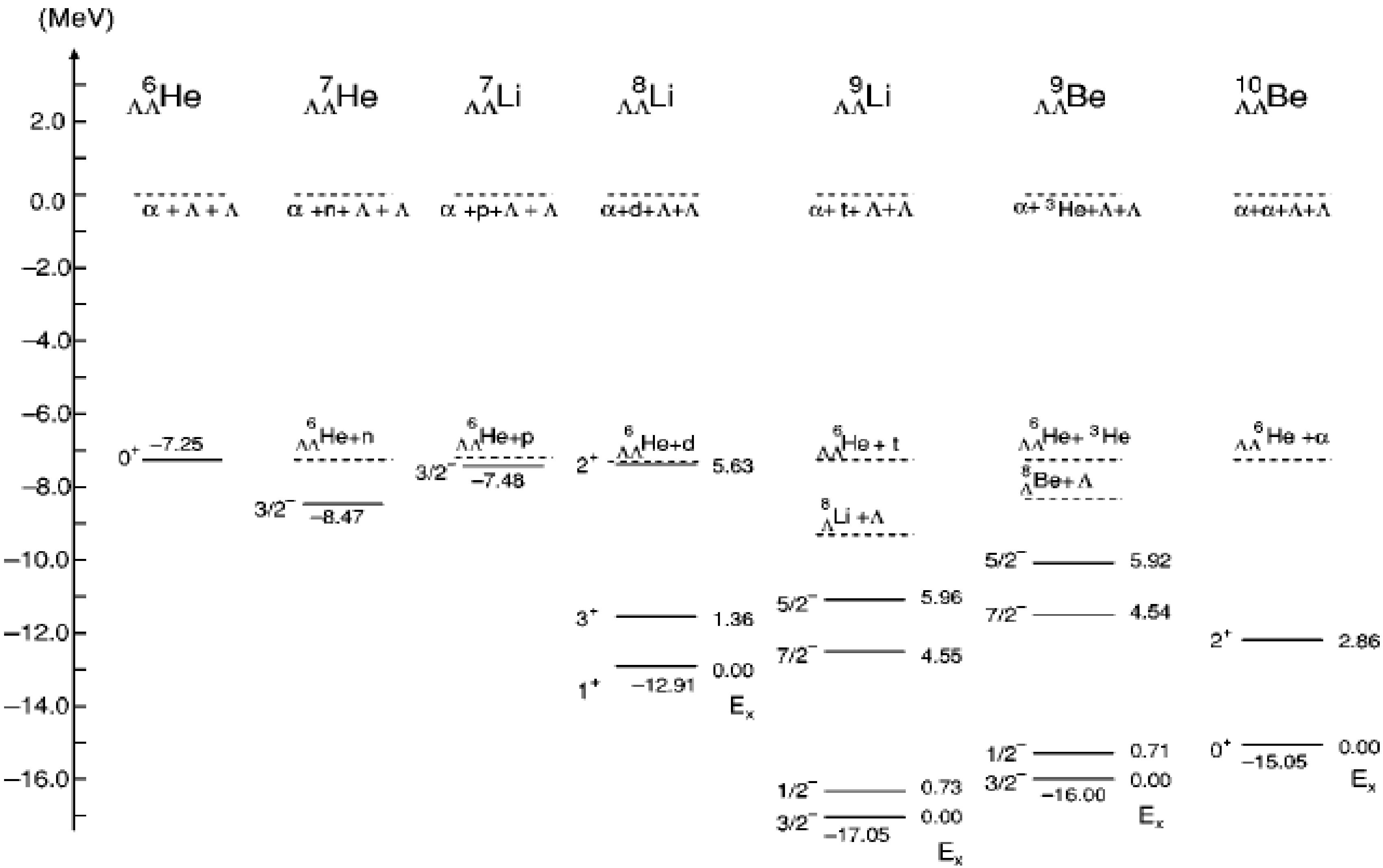
Hiyama et al , proposing to Use 10B target.

4-body cluster model (Hiyama et al, PRC66(2002)

FOUR-BODY CLUSTER STRUCTURE OF $A = 7 - 10$ . . .



Predict many possible bound states

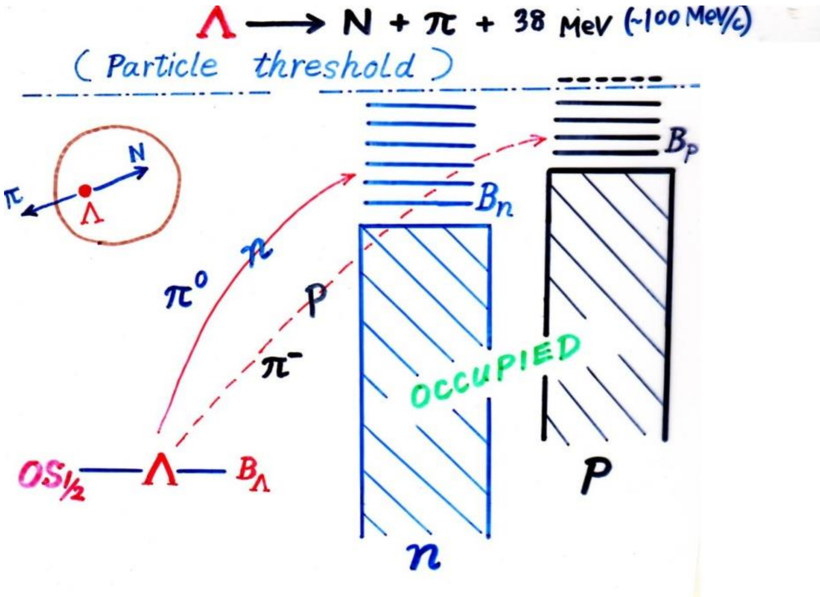


7. Weak decays of hypernuclei

pi-mesonic decay

Nonmesonic decay

4. Mesonic decay of p-shell hypernuclei: The shell model works nicely to explain data.



Increase of nucleon occupation (Pauli blocking) $A \to \infty$

Approx. orthogonality $\langle \psi_N | \phi_\Lambda \rangle \approx 0$

Suppression

Competition

No distortion : $\Gamma_{\pi^0}/\Gamma_\Lambda < 10^{-4}$ for $100 < A$

Pion distortion induces high-q components.

⟶ Restore $\langle \psi_N | \chi_\pi | \phi_\Lambda \rangle$ ← V.R.

Shell & Cluster Structure Effects

Pion distorted waves $\chi_\pi^{(-)*}(q; r)$

solve Klein-Gordon Eq.

Optical potential (MSU group)

J.A. Carr et al. P.R. C25 (1982) 952

effective form :

$$2\omega U_\pi = -4\pi [b_{eff}\, \rho(r) - c_{eff} \nabla \rho(r) \nabla + c_{eff} \frac{\omega}{2M} \nabla^2 \rho(r)]$$

adopted

general form : ⊕ Vertex renormalization

M. Ericson & H. Bandō, P.L. B273 (1990) 169

$$2\omega U_\pi = -4\pi [b(r) + B(r)] + 4\pi \nabla \cdot \{\mathcal{L}(r) [c(r) + C(r)]\} \nabla$$

LLEE

$$-4\pi \{ \frac{p_1 - 1}{2} \nabla^2 c(r) + \frac{p_2 - 1}{2} \nabla^2 C(r) \}$$

$$b(r) = p_1 [b_0 \rho(r) - \epsilon_\pi b_1 \delta \rho(r)]$$

$$c(r) = \frac{1}{p_1} [c_0 \rho(r) - \epsilon_\pi c_1 \delta \rho(r)]$$

$$B(r) = p_2 B_0 \rho(r)^2$$

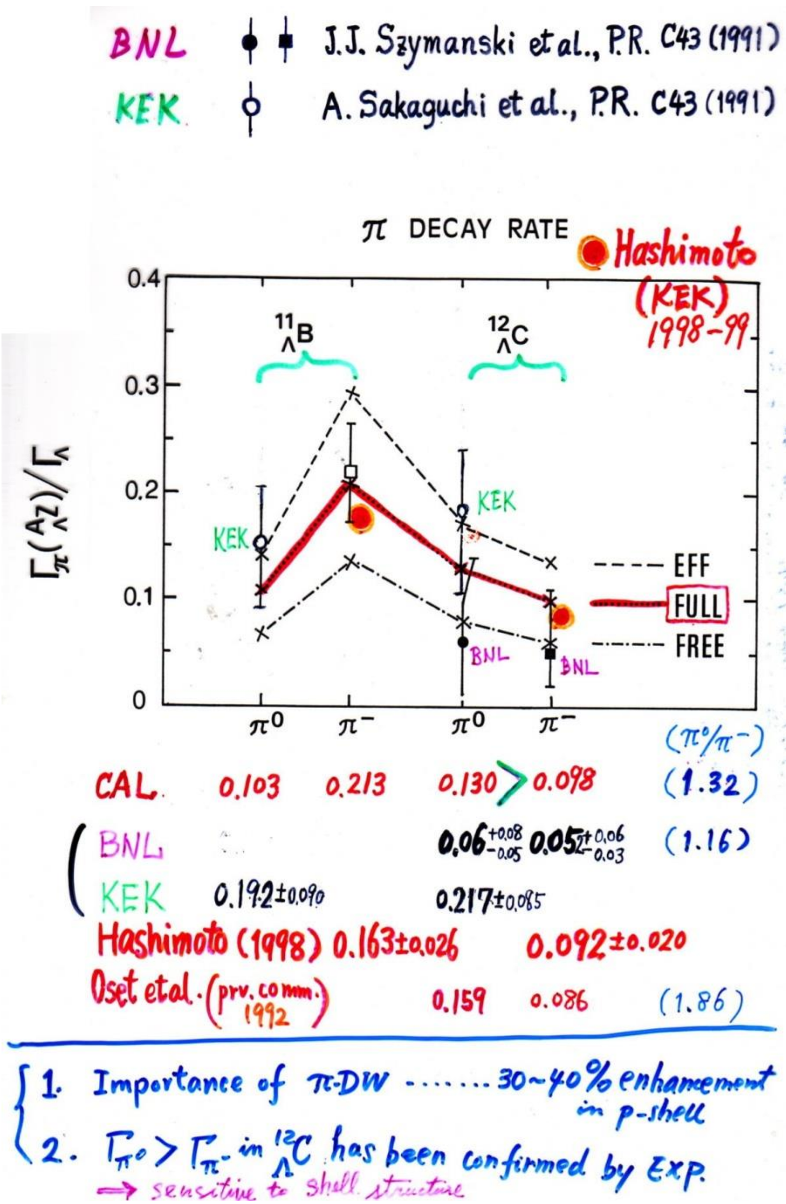
$$C(r) = \frac{1}{p_2} C_0 \rho(r)^2$$

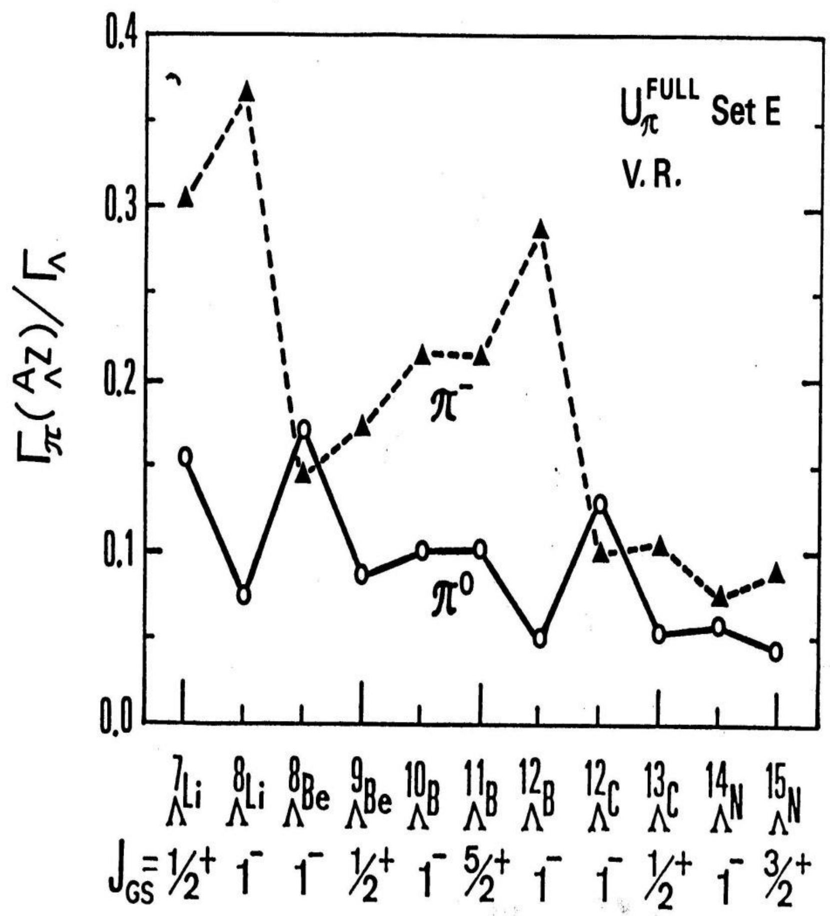
$$\mathcal{L}(r) = \{ 1 + \frac{4\pi}{3} \lambda [c(r) + C(r)] \}^{-1}$$

$L^{(s)}(r) = 1$

$L^{(p)}(r) = \mathcal{L}(r)$

Shell dependence predicted explained.





7. Concluding remarks

1) I reviewed interesting topics selected in hypernuclear spectroscopy , by focusing the relation with production processes.

2) Emphasized novel aspects of many-baryon systems with hyperon(s).

3) I also emphasized importance of producing medium and heavy hypernuclei with good energy resolution.

4) Although I skipped the details of YN interactions,

those experiments will provide with interesting dynamical structures together with YN interaction properties.

Thank you for your attention.