Significance of Detailed Structure Study of Hypernuclei

based on its electro/photoproduction

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(1) Characteristics to be utilized in $^4He(\gamma,K^+)$

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(4) Hyperon s.p.e ($^{208}Pb(\gamma, K^+)_{\Lambda}{}^{208}Al$)

(5) Λ-rotation(deformation) coupling

(6) Summary

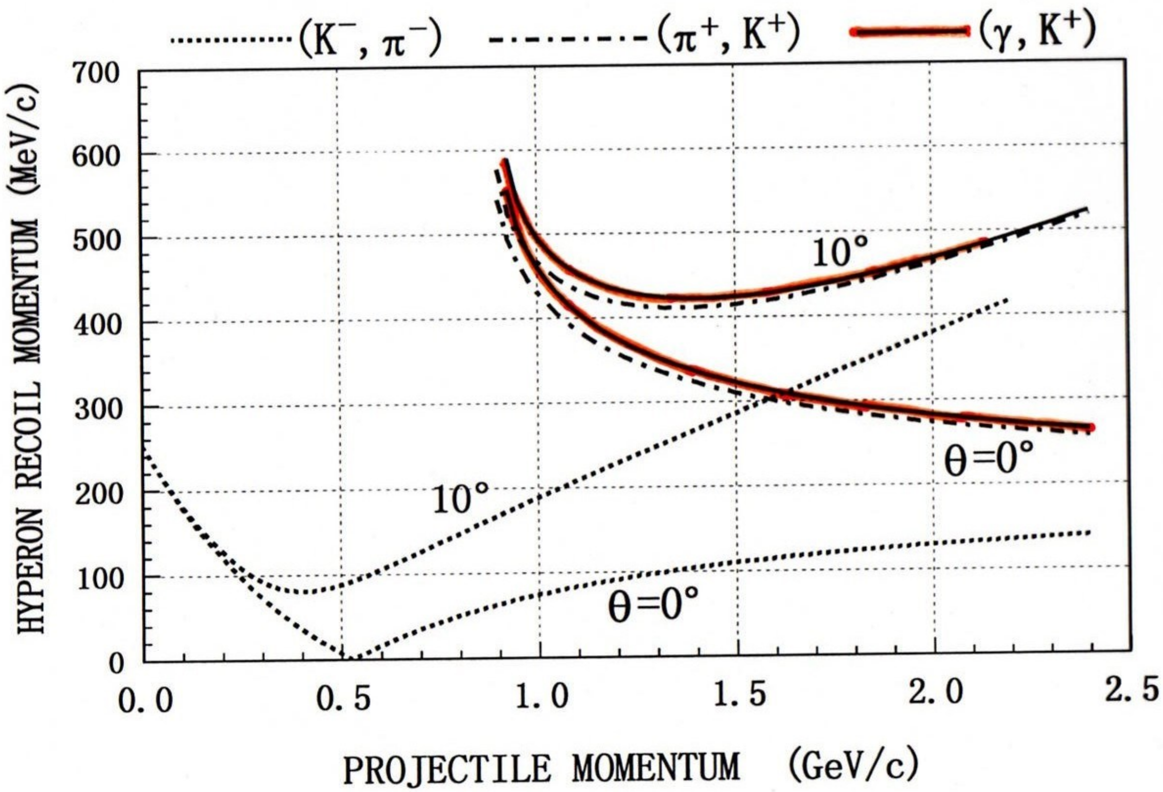
(0) **BASICS:** Hyperon **recoil momentum** and the **transition operator itself** determine the reaction characteristics

(1)

π+n → ΛK+

γp → ΛK+

Momentum transfers are both large and comparable.



q_Λ=350-420 MeV/c at Eγ=1.3 GeV

Microscopic treatment based on the elementary transition amplitudes (π,K) case

$$\frac{d\sigma(\theta_{\rm L})}{d\Omega_{\rm L}} = \gamma \cdot \frac{(2\pi)^4 p_K^2 E_\pi E_K E_H}{p_\pi\{p_K(E_H+E_K) - p_\pi E_K \cos\theta_{\rm L}\}} \overline{|T_{if}^{\rm L}|^2},$$

$$|T_{if}^{\rm L}|^2 = \sum_{M_f} R(if;M_f),$$

$$R(if;M_f) = \frac{1}{[J_i]} \sum_{M_i} \Big| \langle J_f M_f | \int d^3r\, \chi^{(-)}(p_K;r)^* \cdot \chi^{(+)}(p_\pi;r) \times \sum_{k=1}^{A} U_-(k)\, \delta(r-r_k) \cdot \lambda [f + ig(\sigma_k \cdot \hat{n})] | J_i M_i \rangle \Big|^2,$$

(π,K) case

(2) Elementary amplitude N → Y

f = spin-nonflip, *g*= spin-flip , σ= baryon spin

Lab dσ/dΩ photoproduction case (2Lab)

$$\left.\frac{d\sigma}{d\Omega}\right|_{2\mathrm{Lab}} = \frac{(2\pi)^4 p^2 E_K E_\gamma E_\Lambda}{k\{p(E_\Lambda + E_K) - kE_K\cos\theta_L\}} \left|\langle \mathbf{k}-\mathbf{p}, \mathbf{p}|t|\mathbf{k}, 0\rangle_L\right|^2, \quad (2\cdot4)$$

$$\langle \mathbf{k}-\mathbf{p}, \mathbf{p}|t|\mathbf{k}, 0\rangle_L = a_1(\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}) + a_2(\boldsymbol{\sigma}\cdot\hat{\mathbf{k}})(\hat{\mathbf{p}}\cdot\boldsymbol{\epsilon}) + a_3(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})(\hat{\mathbf{p}}\cdot\boldsymbol{\epsilon}) + a_4\{(\hat{\mathbf{k}}\times\hat{\mathbf{p}})\cdot\boldsymbol{\epsilon}\}. \quad (2\cdot5)$$

spin non-flip term

$$\langle \mathbf{k}-\mathbf{p}, \mathbf{p}|t|\mathbf{k}, 0\rangle_L = \epsilon_0(f_0 + g_0\sigma_0) + \epsilon_x(g_1\sigma_1 + g_{-1}\sigma_{-1})$$

Spin-flip terms

Combination of photon polarization and baryon spin

with definitions of the coefficients:

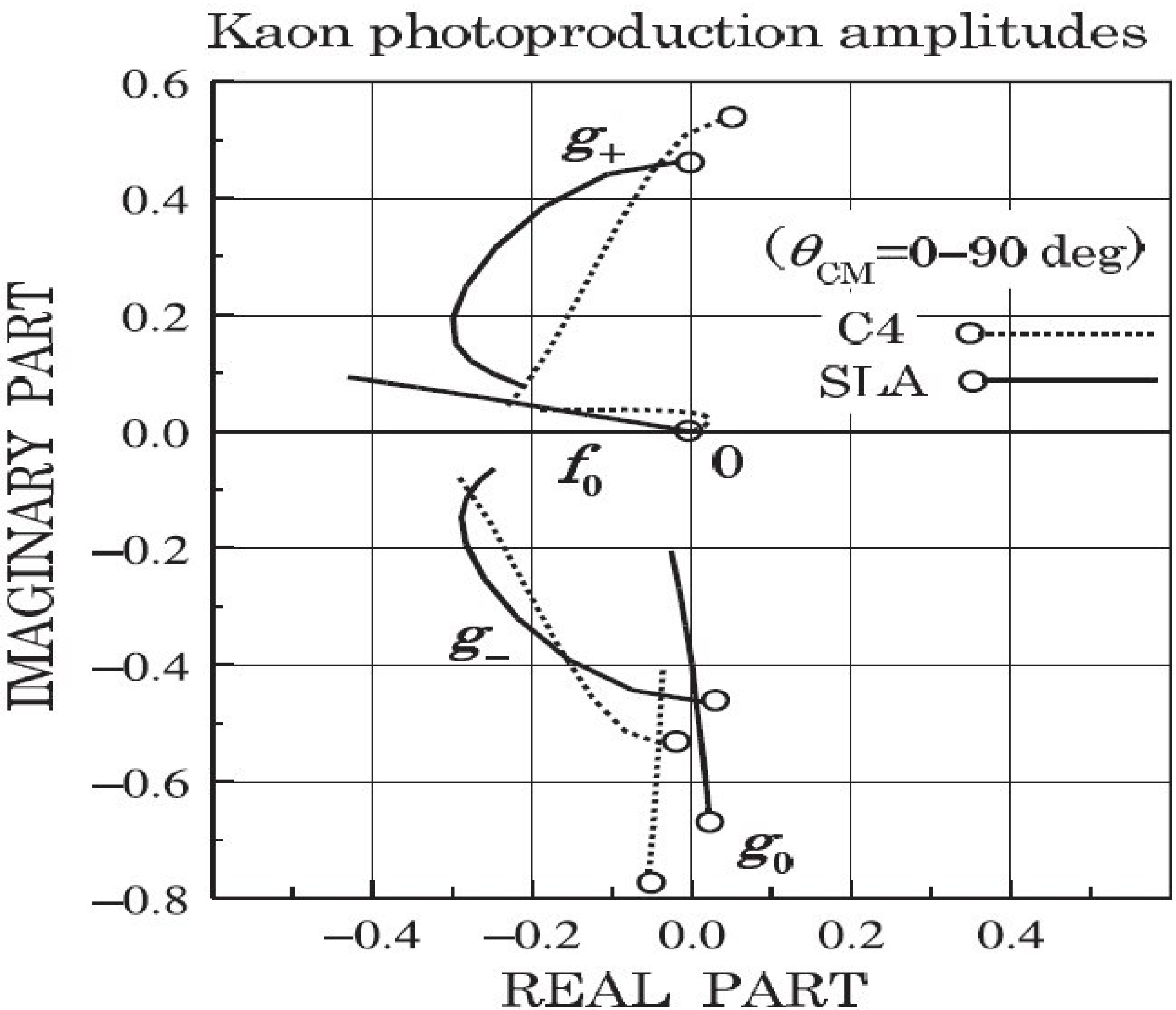
$$f_0 = a_4\sin\theta_L,$$

$$g_0 = a_1,$$

$$g_{\pm1} = \frac{1}{\sqrt{2}}\{\mp(a_1 + a_3\sin^2\theta_L) - i\sin\theta_L(a_2 + a_3\cos\theta_L)\}. \quad (2\cdot12)$$

(γ,K+) case

Elementary amplitudes (complex and p-dependent, θ-dependent)



Three spin-flip terms are all large in Kaon photoproduction

(1) Application to the lightest closed-shell target ^{4}He
(A proposal from theory side)

Unique role of (e,e'K$^+$) or (γ,K$^+$) reaction:

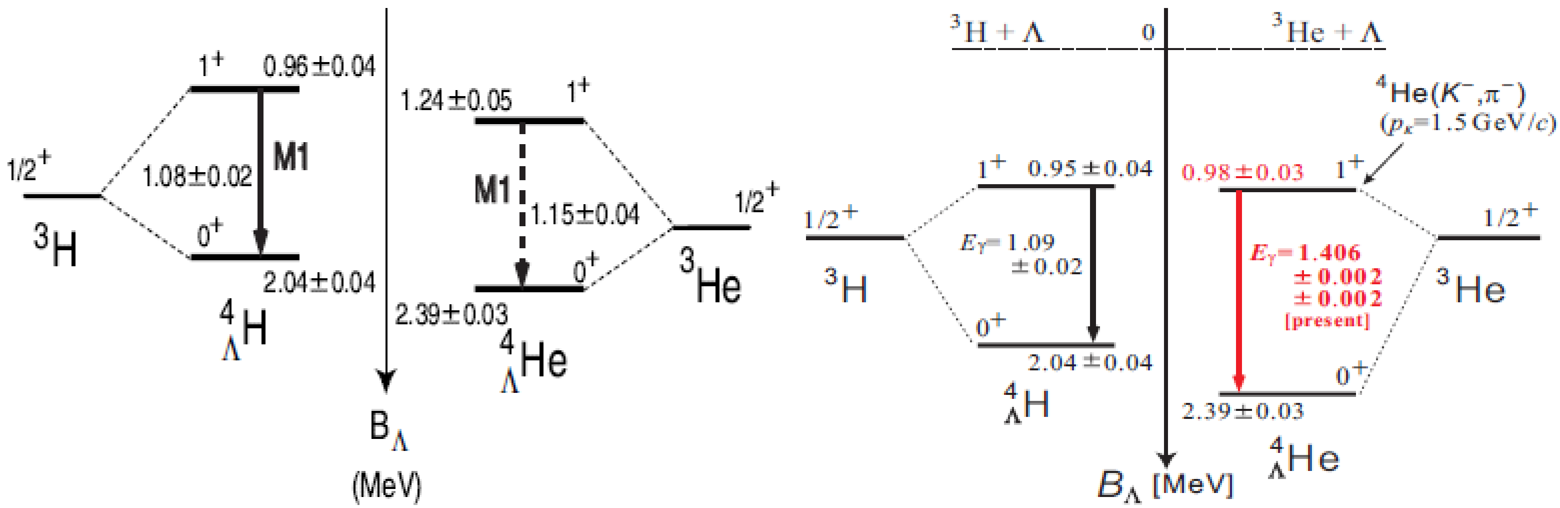
to excite $^4_\Lambda$H(1+) state preferentially by making use of the spin-flip dominant nature.

(An important issue is to determine 1+ energy position (update) for the study of CSB effect in Λ-N interaction.)

(Taken from A. Gal (J-PARC Hadron Phys. Workshop (2016.3)

${}^4_\Lambda$H–${}^4_\Lambda$He levels before and after J-PARC E13 exp.

T. O. Yamamoto et al., J-PARC-E13, PRL 115 (2015) 222501



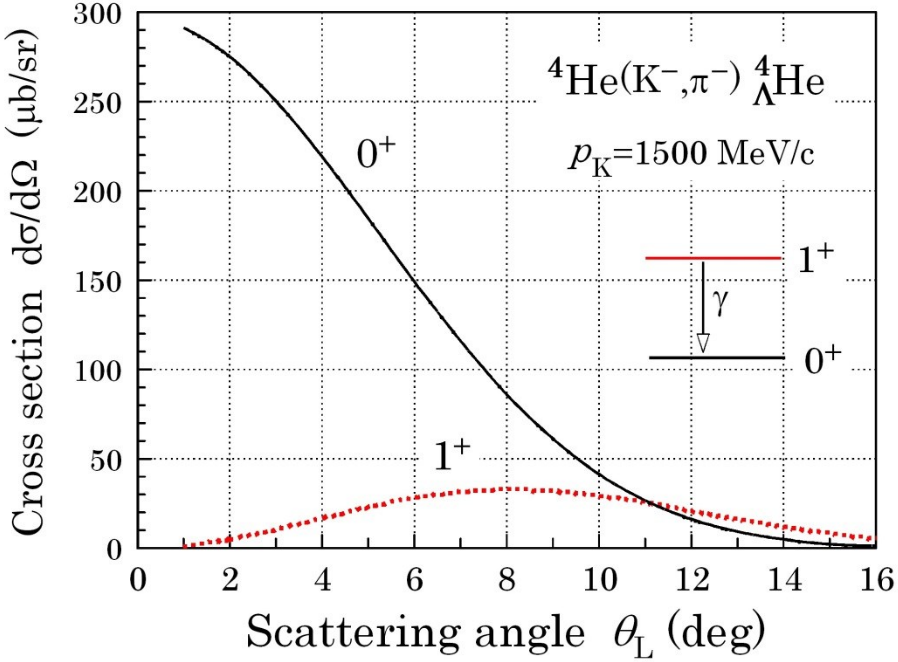
MAMI's new value $B_\Lambda({}^4_\Lambda\mathrm{H})=2.12\pm0.01\pm0.09$ MeV, consistent with emulsion value, obtained by measuring decay π^- in ${}^4_\Lambda\mathrm{H}\rightarrow{}^4\mathrm{He}+\pi^-$ [PRL 114 (2015) 232501].

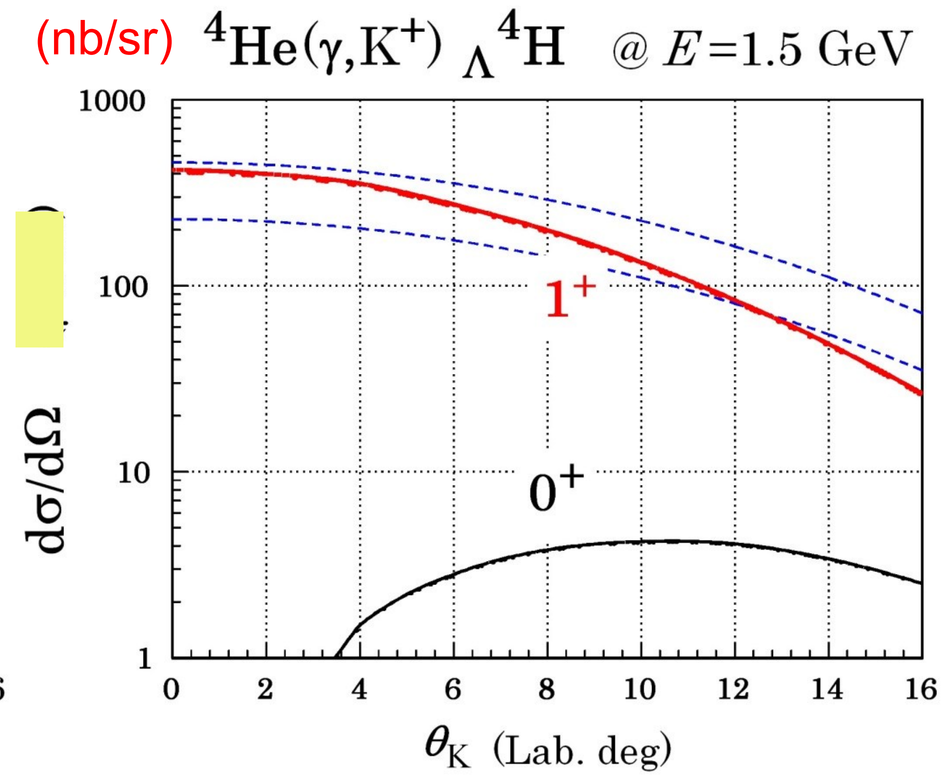
CSB is strongly spin dependent, dominantly in $0^+_{\mathrm{g.s.}}$

350 ± 60 keV in ${}^4_\Lambda$H-${}^4_\Lambda$He vs. ≈-70 keV in ^{3}H-^{3}He.

$^4He(K^-,\pi^-)$ vs. $^4He(\gamma,K^+)$

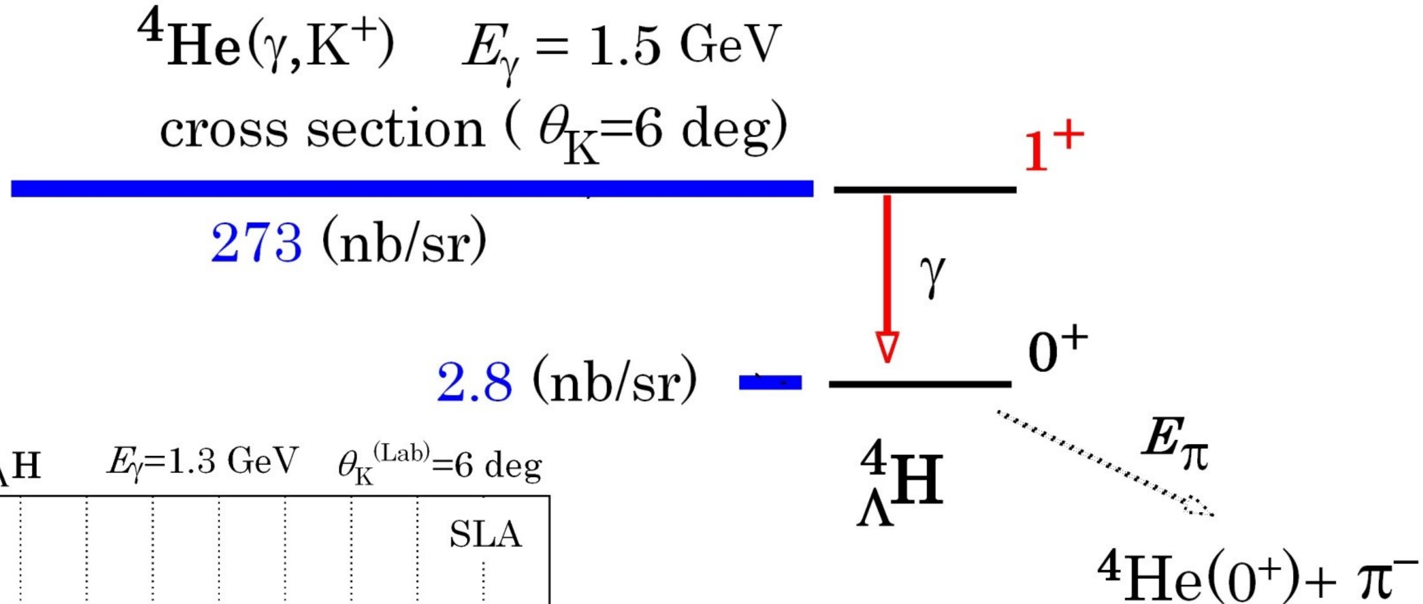
(A reaction theoretical view)

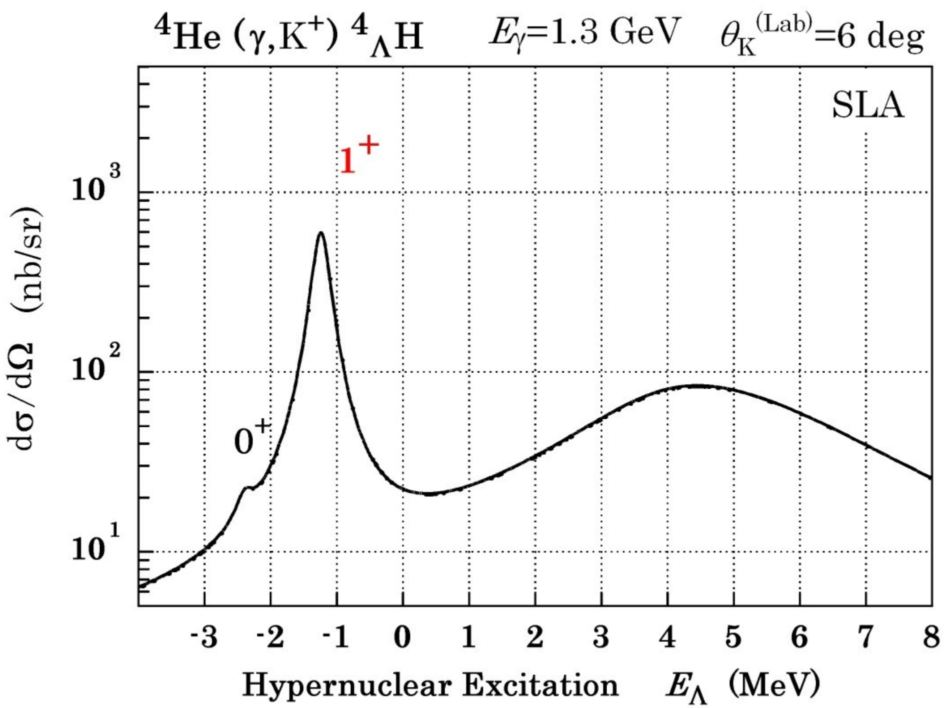




1^+ gets minor XS, but it is excited anyway, then (K,πγ) coincidence method successful. → Tamura's talk

XS(1+) is far predominantly larger than XS(0+)





Measure weak decay π energy:
(T=53.24)
p=133.03 MeV/c

In fact **Mainz did it, but energy resolution is not enough.**

E(1+) peak energy will be determined precisely @Jlab by ^{4}He(*e*,*e*′*K*+)

(2) JLab (e,e'K+) experiments opened a new stage of high precision hypernuclear reaction spectroscopy

- Success of JLab experiments (Hall A & C) on p-shell targets ---- E resolution **~0.54MeV**
- Suggesting new theoretical aspects

The most typical one: ^{12}C(e,e'K+)

Tang et al. PRC 90(2014) Hall C experiment

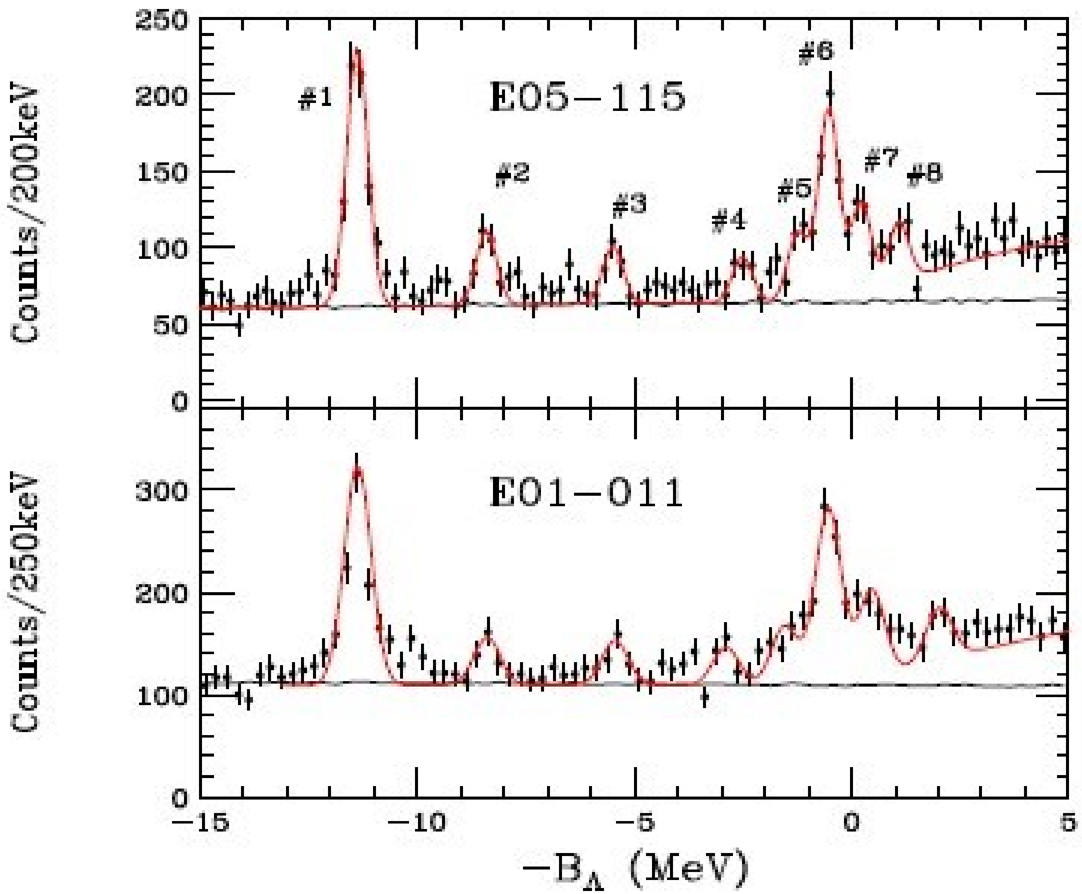
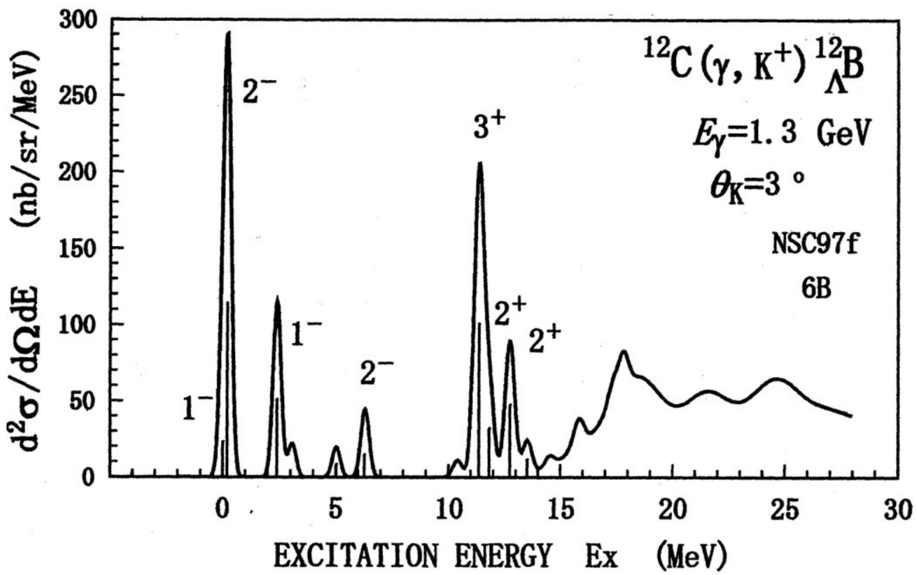
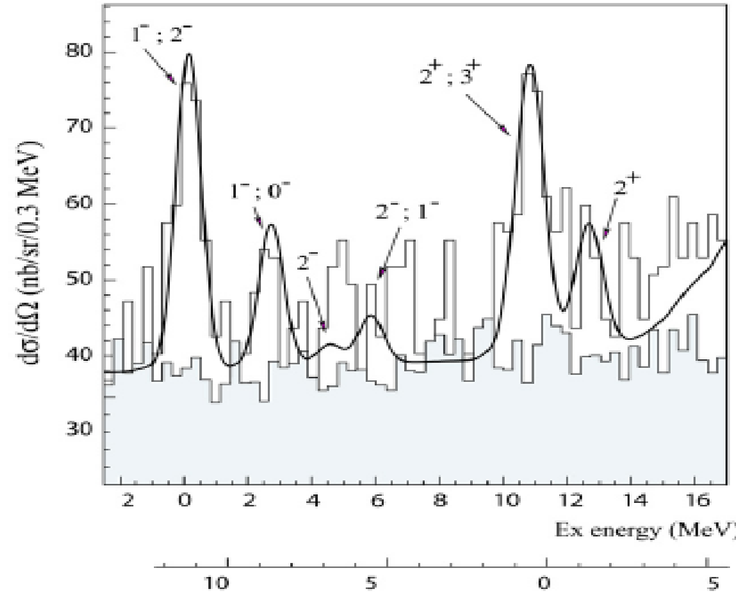


FIG. 10. (Color online) Spectroscopy of $^{12}_{\Lambda}B$ from the E05-115 and E01-011 experiments. The area below the black line is the accidental background.

Theor. prediction confirmed by (e,e'K$^+$) exp.

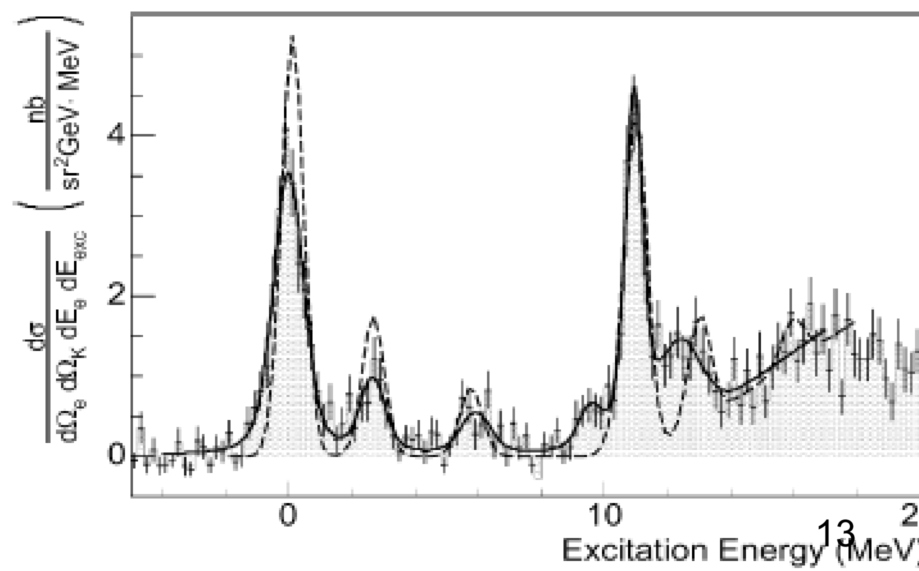




Motoba. Sotona, Itonaga,
Prog.Theor.Phys.Sup.**117** (**1994**)
T.M. *Mesons & Light Nuclei* (2000)
updated w/NSC97f.

--→

Hall C (up) T. Miyoshi et al.
*P.R.L.***90** (2003) 232502. **Γ=0.75keV**
Hall A (bottom), J.J. LeRose et al.
N.P. A**804** (2008) 116. **Γ=0.67keV**



Exp XS and DWIA estimates: are in good agreement.
The present theor. treatment -- proved to be powerful.

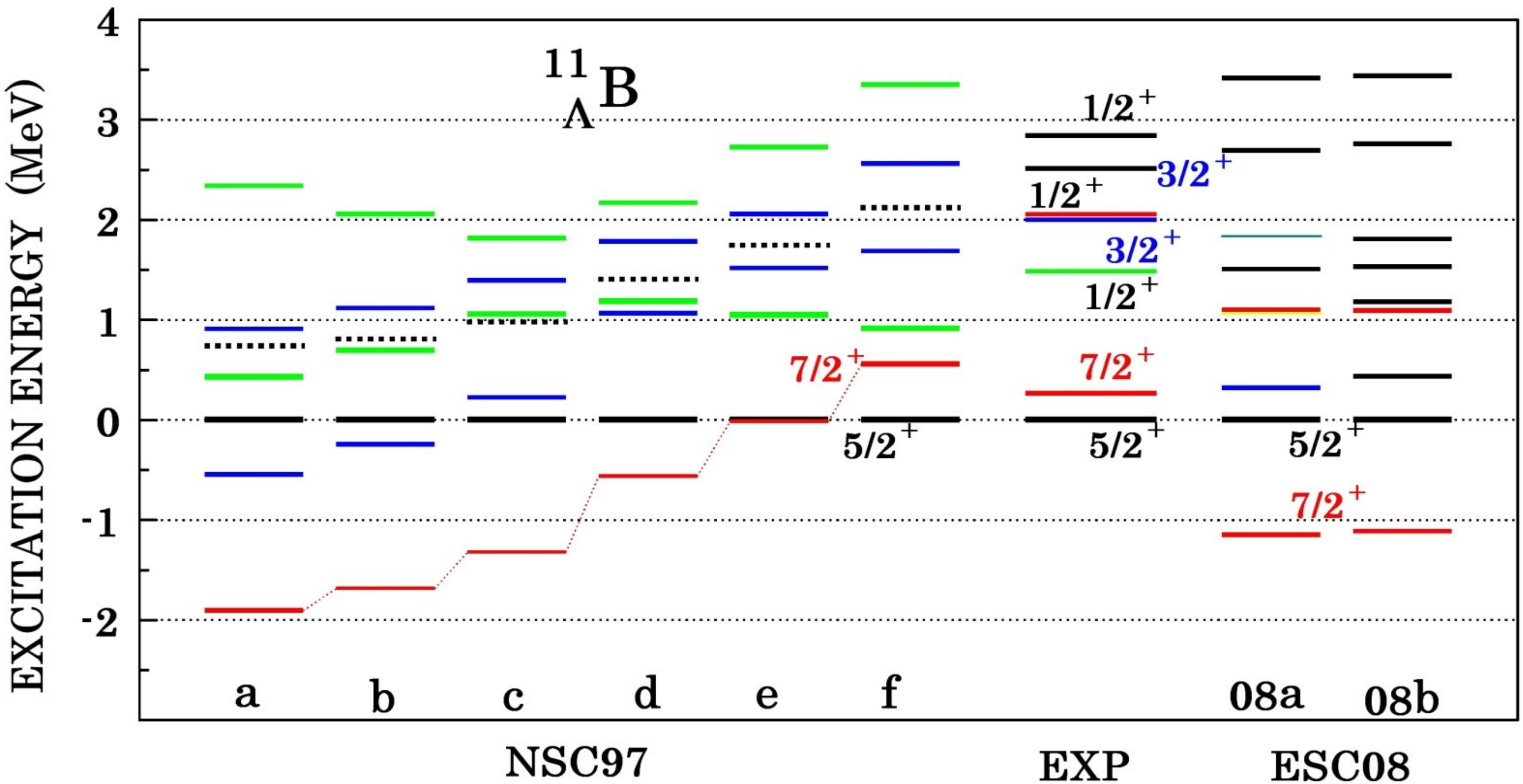
12C(γ,K+) Cross sec. calculated in DWIA at E_γ = 1.5GeV, θ_K(Lab)=7deg

(Relative strengths with respect to the ground-state peak are also shown for reference)

Table I. Comparison of excitaion energies of $^{12}_{\Lambda}$B and its photoproduction cross sections $d\sigma/d\Omega$ (nb/sr)

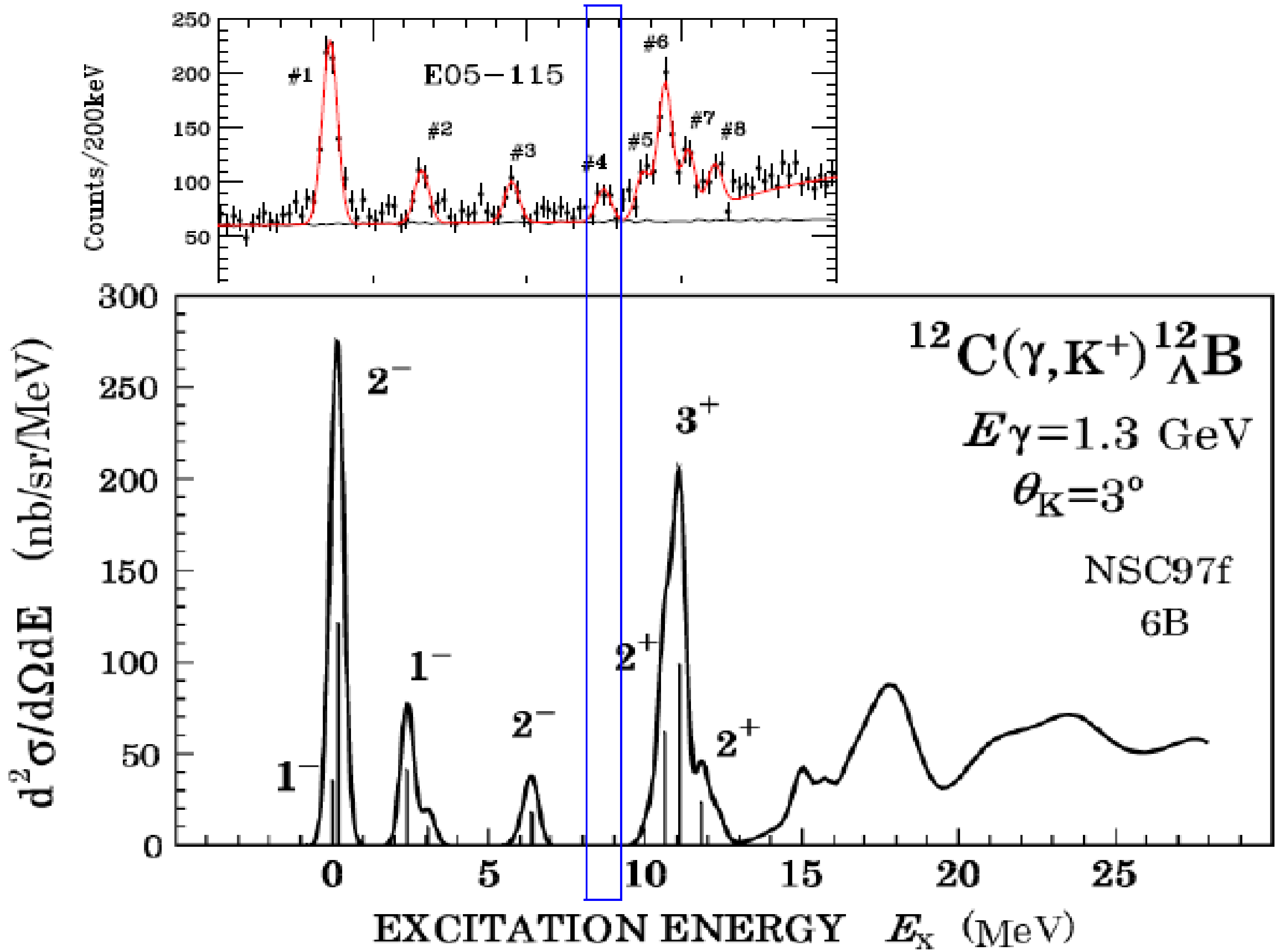
Experiment				Theory with NSC97f			
Peak	$-B_\Lambda$(MeV)	E_x (MeV)	$d\sigma/d\Omega$	J_i	E_x (MeV)	$d\sigma/d\Omega$	Sum
# 1-1	−11.524	GS(0.0)		1^-_1	GS(0.0)	21.04	
# 1-2	−11.345	(0.179)	101.0	2^-_1	(0.186)	89.33	100.37
# 2	−8.415	(3.109)	33.5	1^-_2	(2.398)	48.44	56.10
				0^-_1	(3.062)	7.66	
				2^-_2	(5.022)	6.96	
# 3	−5.475	(6.049)	26.0	2^-_3	(6.267)	11.84	23.82
				1^-_3	(6.389)	5.02	
# 5	−1.289	(10.235)	31.5	2^+_1	(11.000)	1.33	9.49
				1^+_1	(11.120)	8.16	
# 6	−0.532	(10.992)	87.7	3^+_1	(11.081)	77.56	130.73
				1^+_1	(11.610)	53.17	
				1^+_2	(12.129)	6.08	
# 8	0.973	(12.497)	28.5	2^+_3	(12.784)	19.96	29.95
				1^+_3	(13.176)	3.74	

Nijmegen B-B interaction model improved by taking account of hypernuclear reaction **data+γ**



Thus high precision reaction data, together with γ, help us discriminate several versions of Y-N interaction models.

Emphasize: detailed comparison discloses a new feature of hypernuclear structure



Our new theoretical challenge

is to take both parity states into account.

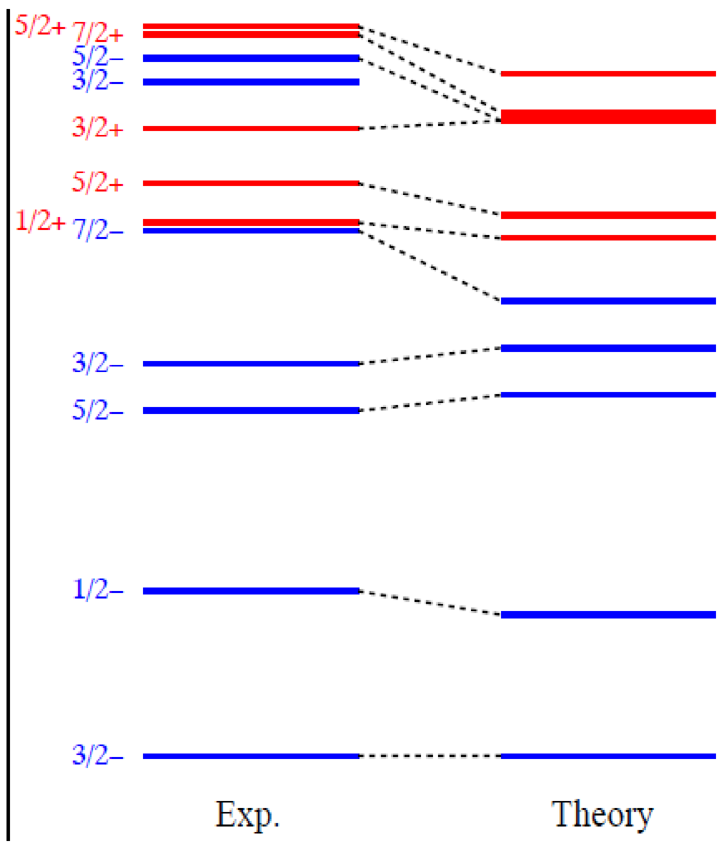
"*parity-mixing" mediated by* Λ

that is a new concept seen only in hypernucleus

$$^{12}{}_{\Lambda}\mathrm{B}(J_{\mathrm{H}}^{-}) = \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{-})_0 \times \Lambda_s \}^{(0)} + \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{+})_1 \times \Lambda_p \}^{(2)}$$

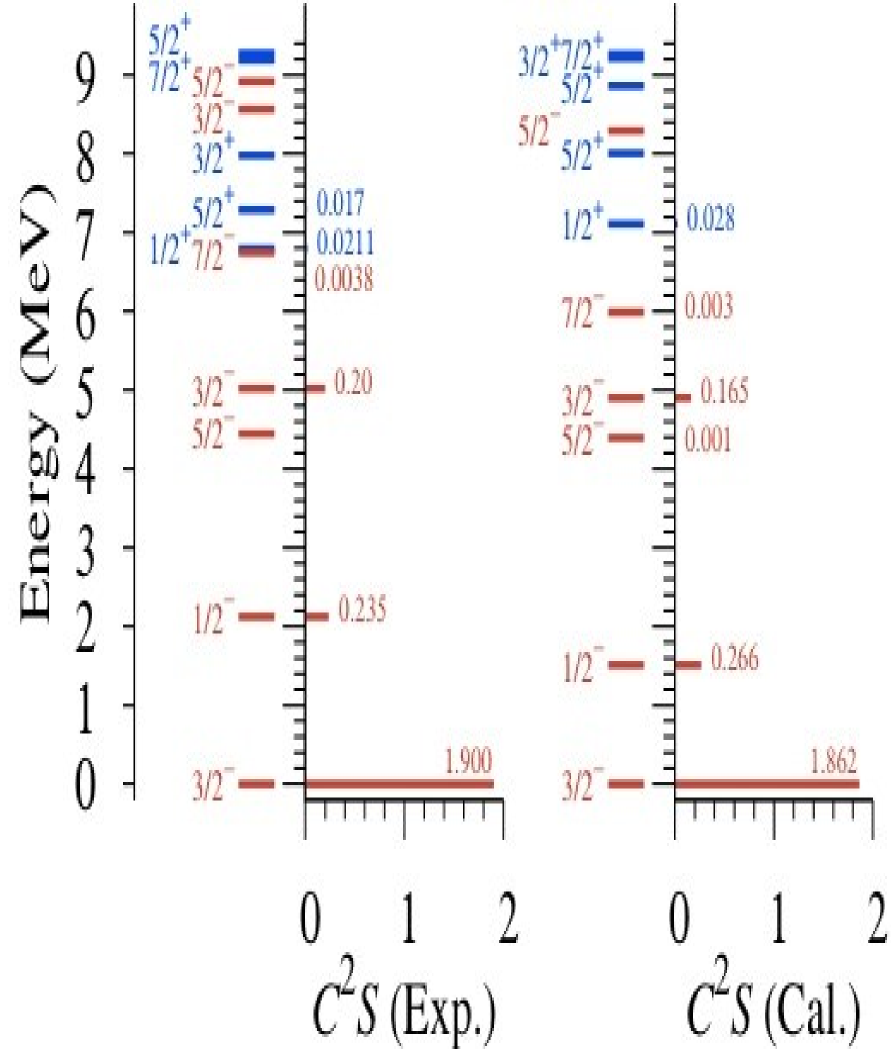
$$^{12}{}_{\Lambda}\mathrm{B}(J_{\mathrm{H}}^{+}) = \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{-})_0 \times \Lambda_p \}^{(1)} + \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{+})_1 \times \Lambda_s \}^{(1)}$$

There are opposite parity excited states at low energy E<10MeV. (Many theoretical attempts)



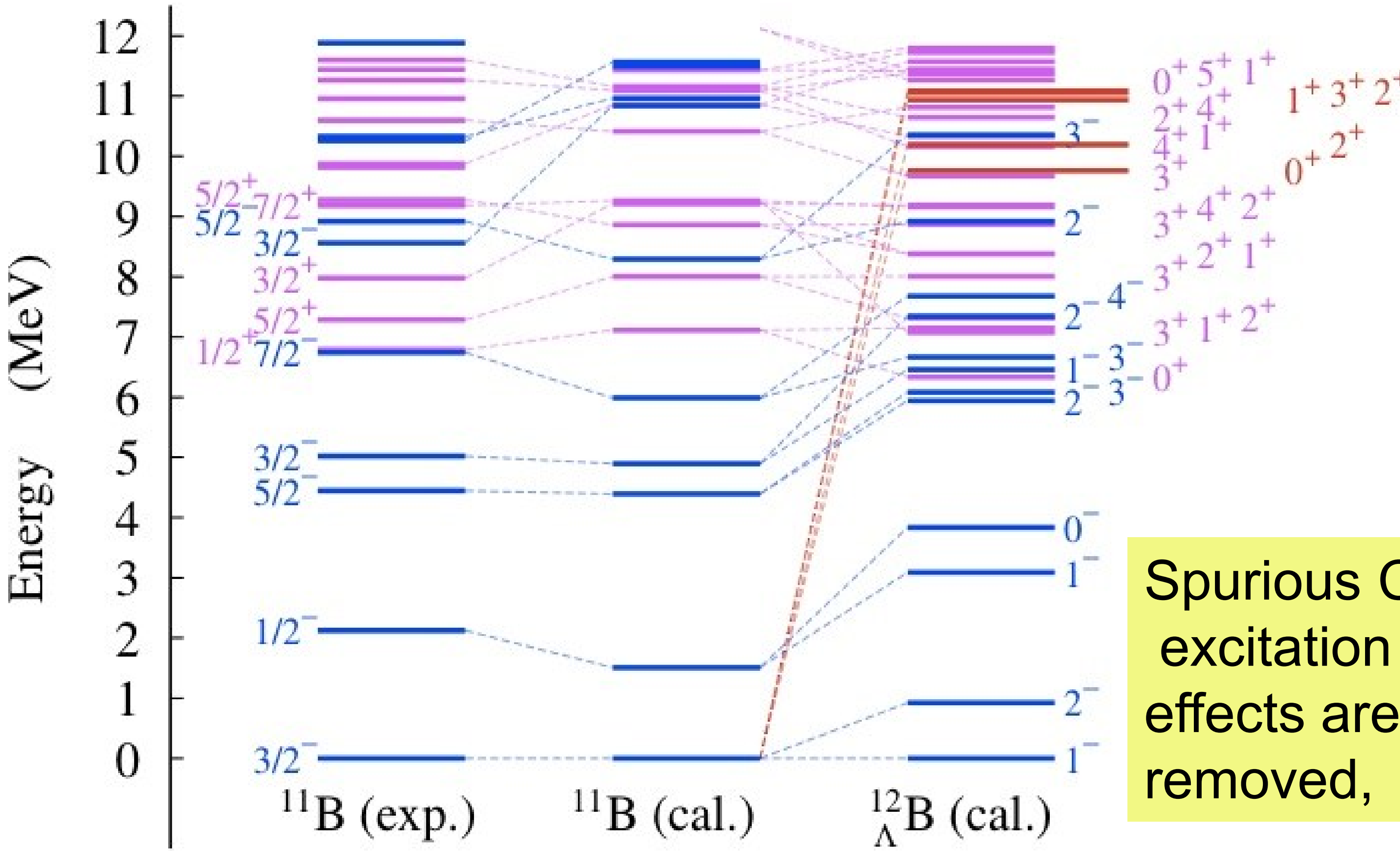
^{11}B

(2015.05.10 Umeya)



Proton pickup S-factor

“Parity-mixing” extended calculation (preliminary)



Spurious C-M excitation effects are removed,

Components connected via (γ,K$^+$)

proton is converted --→ Λ in s or p orbits

(So far only green arrows are taken into account.)

$$^{12}{}_{\Lambda}B(J_H^-) = \{([s^4]p^7; J_C^-)_0 \times \Lambda_s\}^{(0)} + \{([s^4]p^6(sd)^1; J_C^+)_1 \times \Lambda_p\}^{(2)} + \{([s^3]p^8; J_C^+)_1 \times \Lambda_p\}^{(2)}$$

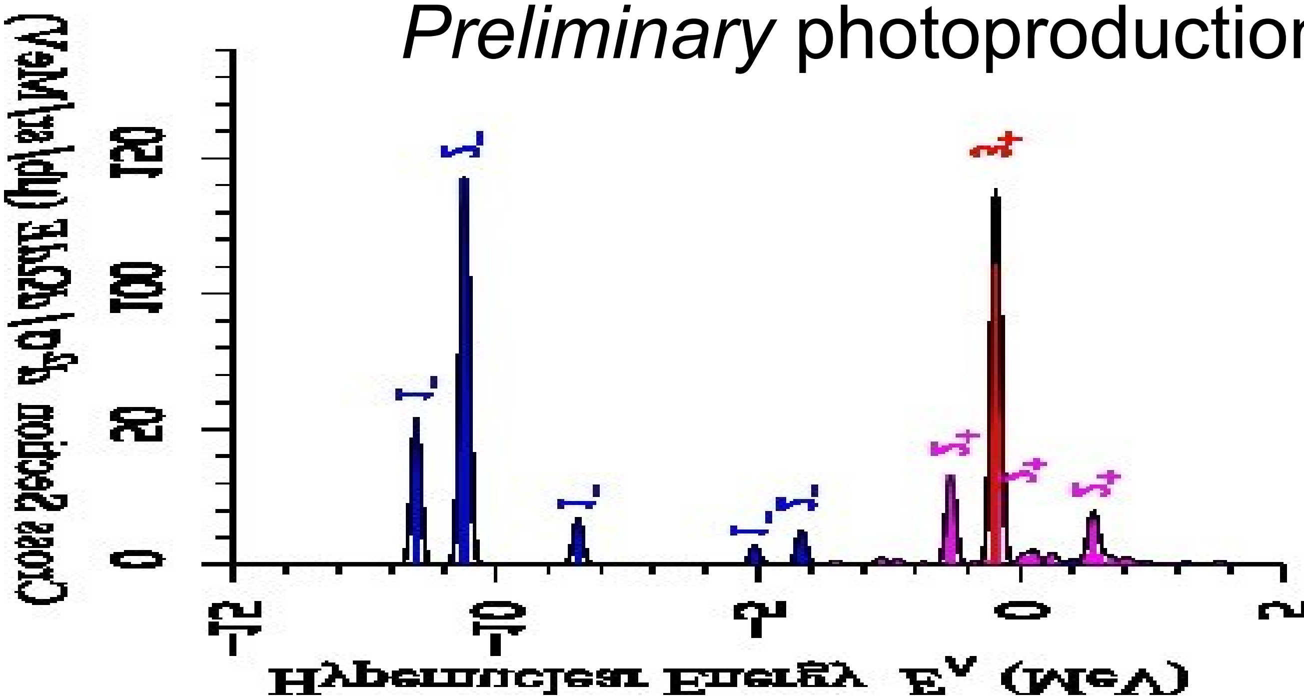
$$^{12}C(0^+)_{0+2h\omega} = |[s^4]p^8\rangle + |[s^4]\, p^7(fp)^1\rangle + |[s^4]p^6(sd)^2\rangle + |[s^3]p^8(sd)^1\rangle + |[s^2]p^{10}\rangle$$

$$^{12}{}_{\Lambda}B(J_H^+) = \{([s^4]p^7; J_C^-)_0 \times \Lambda_p\}^{(1)} + \{([s^4]p^6(sd)^1; J_C^+)_1 \times \Lambda_s\}^{(1)} + \{([s^3]p^8; J_C^+)_1 \times \Lambda_s\}^{(1)}$$

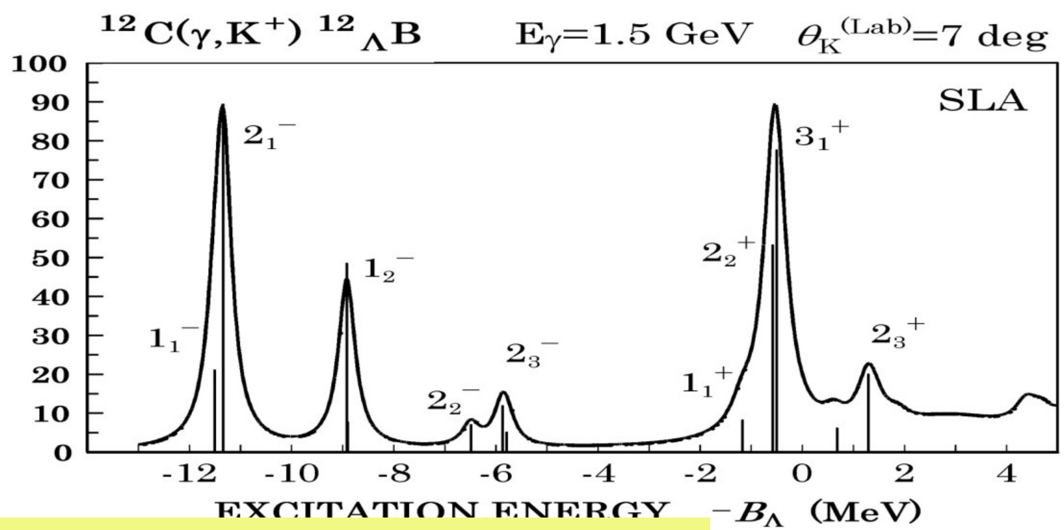
Problems:

What kind of effective interactions should be used in describing those WF in the extended model space.

Preliminary photoproduction X-S



Down: Previous calculation



Careful claculation is in progress

(3) Medium-heavy nuclear targets

A typical example of medium-heavy target : **^{28}Si:** $(d_{5/2})^6$ and $(sd)^{6P}(sd)^{6N}$

to show characteristics of the (γ,K^+) reaction with DDHF w.f.

Spin-orbit splitting:
consistent with ${}_{\Lambda}{}^{7}$Li, ^{9}Be, ^{13}C, ^{89}Y

These ***characteristic merits*** *of the* $\gamma p \to \Lambda K^+$ *process*
(ability of exciting selectively high-spin unnatural-parity states)
should be realized ***better in heavier systems*** *involving large* j_p *and large* j_Λ

$(e,e'K^+)$ $\quad d^3\sigma/dE_e\, d\Omega_e\, d\Omega_K = \Gamma \times$ $\mathbf{d\sigma/d\Omega_K}$

Γ : virtual photon flux (kinematics)

Hereafter we discuss $\mathbf{d\sigma/d\Omega_K}$ for ${}^{A}Z\,(\gamma,K+)_{\Lambda}{}^{A}Z'$

Theor. x-section for $(d_{5/2})^6\ (\gamma,K^+)[j_h-j_\Lambda]J$

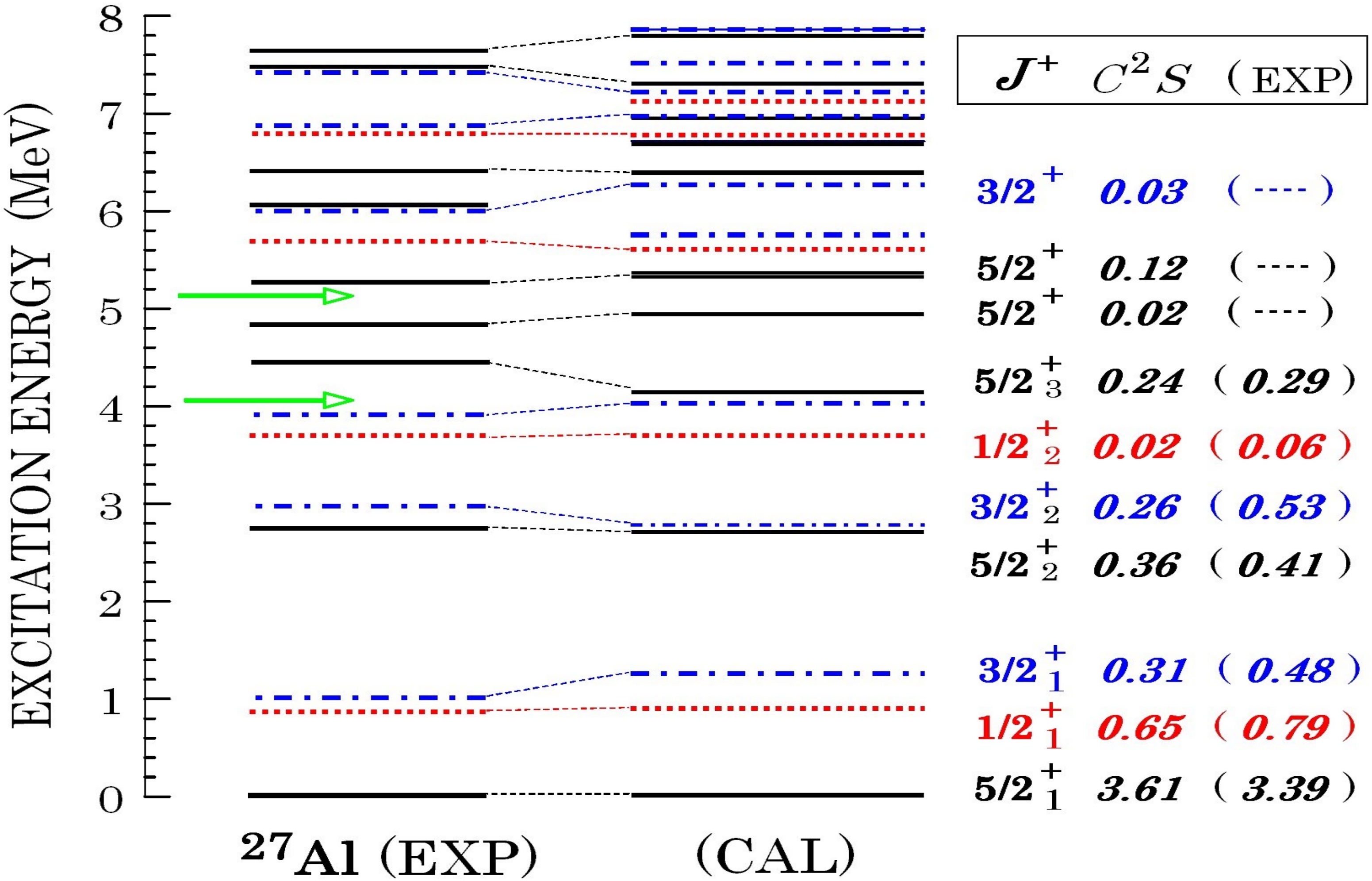
DWIA [nb/sr]

Proton hole	Lambda= s1/2L (-16.92)	p3/2L (-8.40)	p1/2L (-8.40)	1s1/2L (0.32)	d5/2L (0.69)	d3/2L (0.69)
d5/2 (-16.17)	2+ 29.2 3+ 63.8 (g.s.)	1- 5.4 2- 7.1 3- 4.2 4- 141.8	2- 19.4 3- 76.2	2+ 2.2 3+ 4.6	0+ 0.0 1+ 26.0 2+ 0.3 3+ 26.7 4+ 0.5 5+ 164.1	1+ 8.9 2+ 34.9 3+ 30.4 4+ 112.0
p1/2 (-25.49)	0- 9.4 1- 30.5	1+ 2.0 2+ 66.9	0+ 0.0 1+ 28.3	0- 3.7 1- 12.2	2- 10.7 3- 76.9	1- 1.4 2- 43.5
p3/2 (-29.84)	1- 14.3 2- 59.1	0+ 0.0 1+ 8.9 2+ 0.4 3+ 109.1	1+ 1.8 2+ 62.5	1- 5.9 2- 24.8	1- 3.2 2- 4.5 3- 4.5 4- 148.6	0- 2.0 1+ 5.7 2+ 17.5 3+ 96.3
s1/2 (-44.55)	0+ 0.1 1+ 19.2	1- 12.1 2- 50.0	0- 7.3 1- 23.7	0+ 0.3 1+ 51.4	2+ 27.0 3+ 58.1	1+ 16.5 2+ 40.1

Proton pickup from $^{28}Si(0^+):(sd)^6 = (d_{5/2})^{4.1}(1s_{1/2})^{0.9}(d_{3/2})^{1.0}$

Another important factor in the structure analysis (reaction): **WF**

Nuclear core excitations should be carefully taken into account.



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Early example: How to understand ${}_{\Lambda}^{89}$Y data

(Hotchi et al, PRC 64 (2001)) vs. CAL(Motoba et al, 1988)

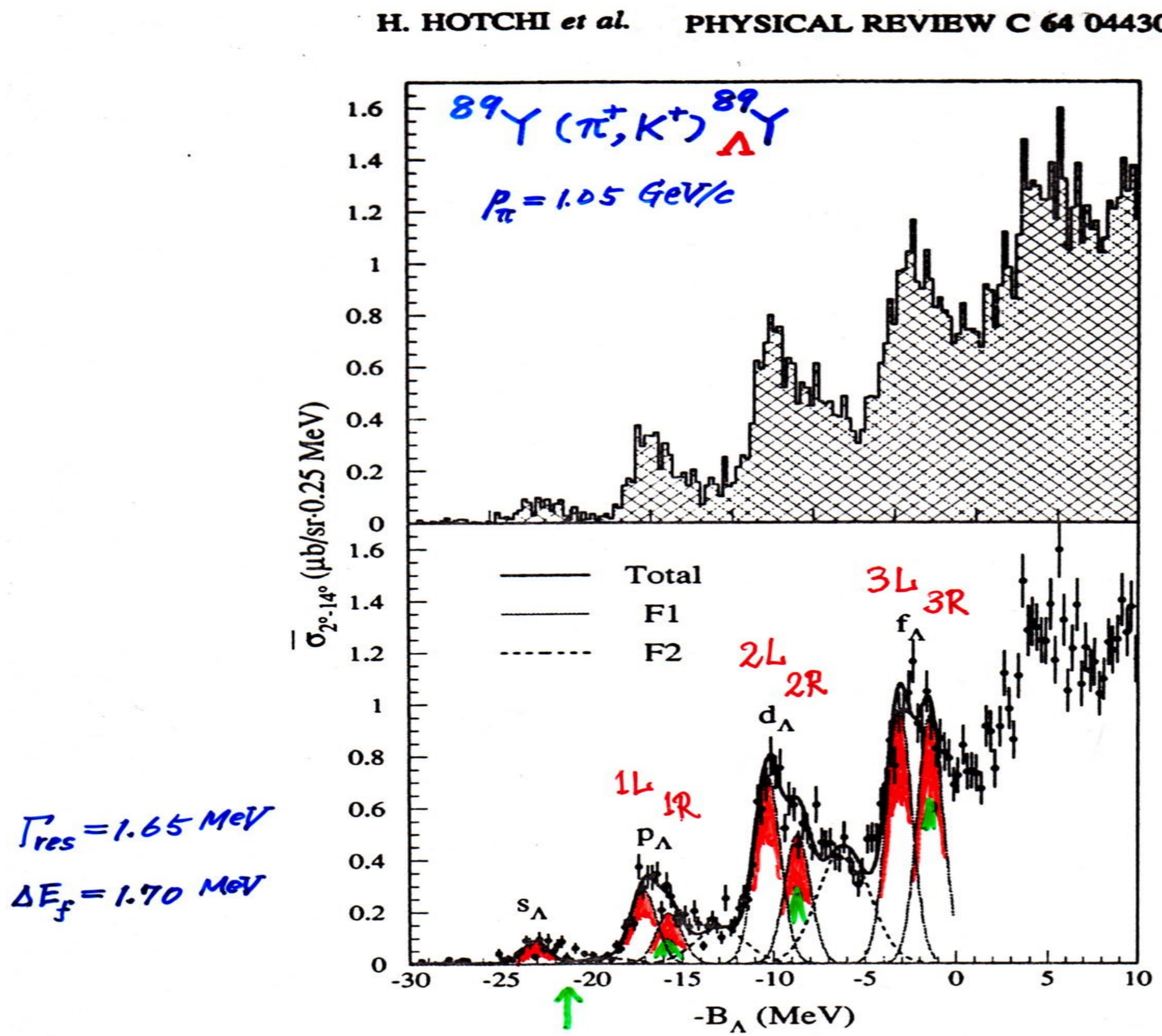
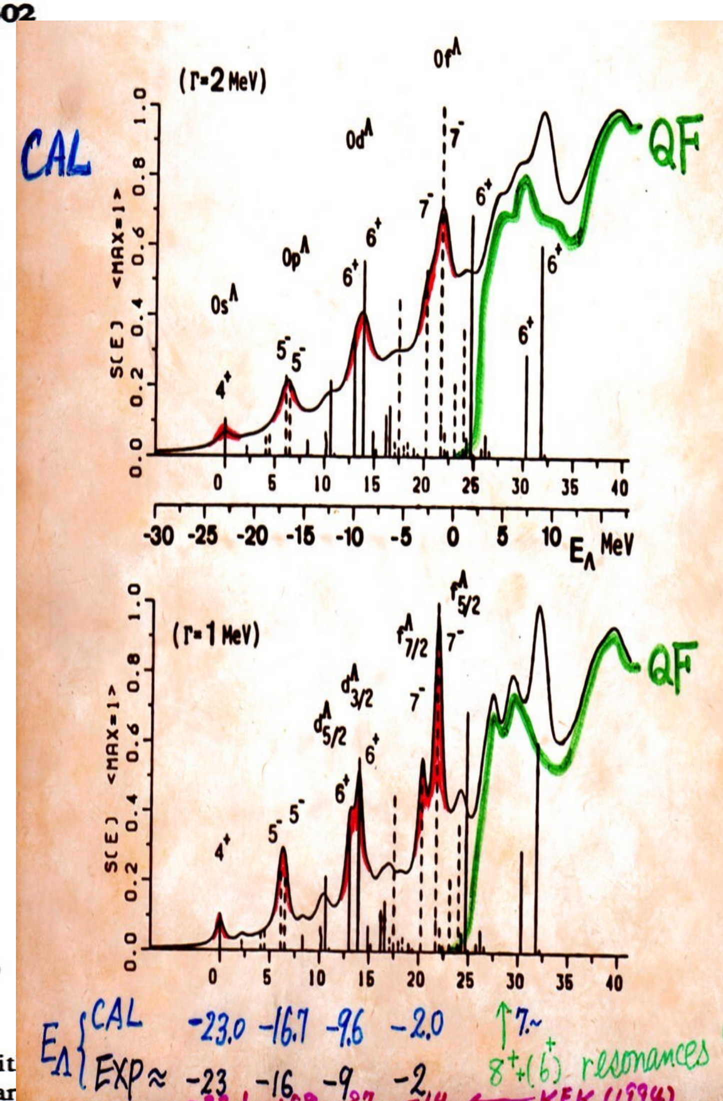
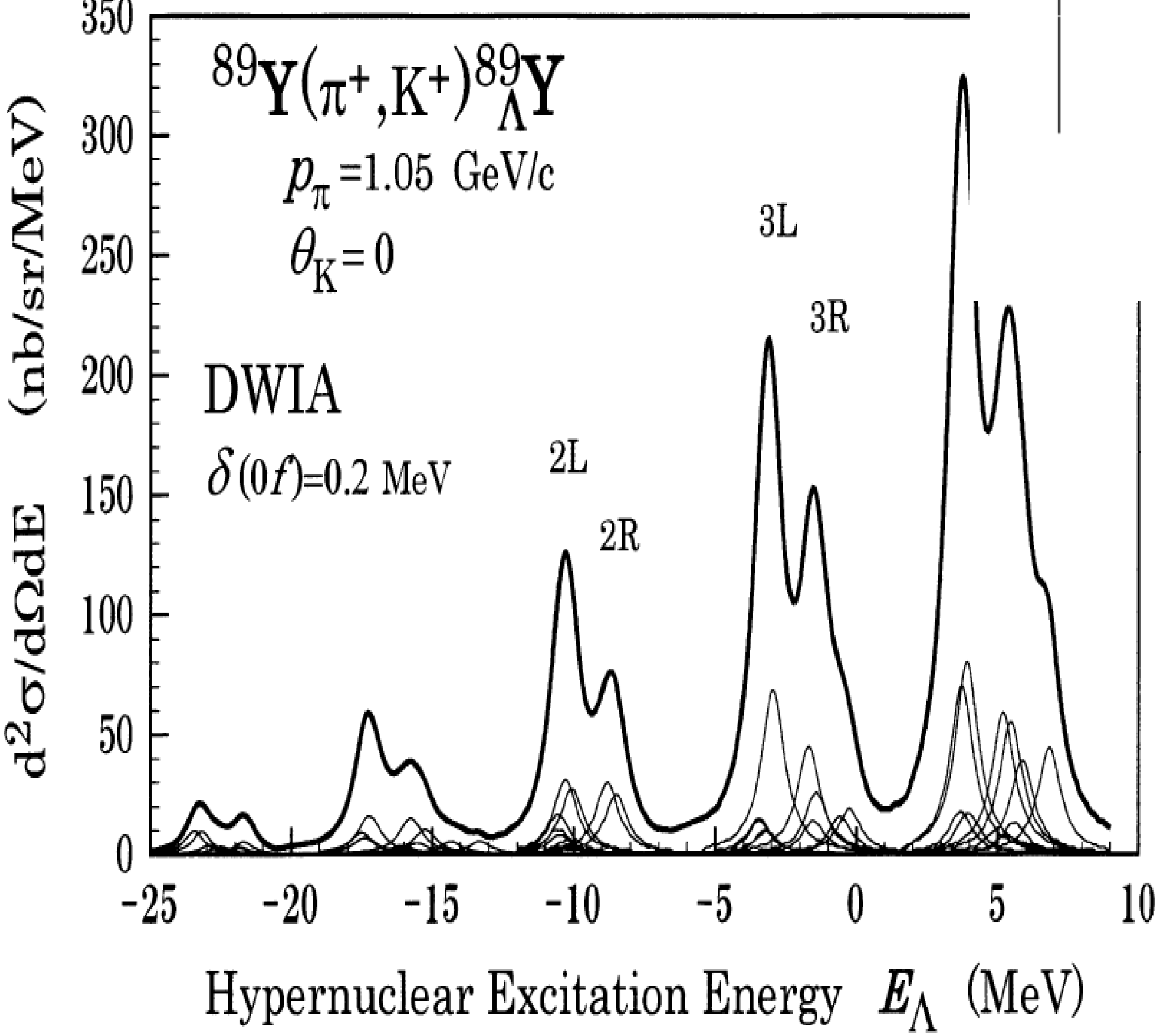
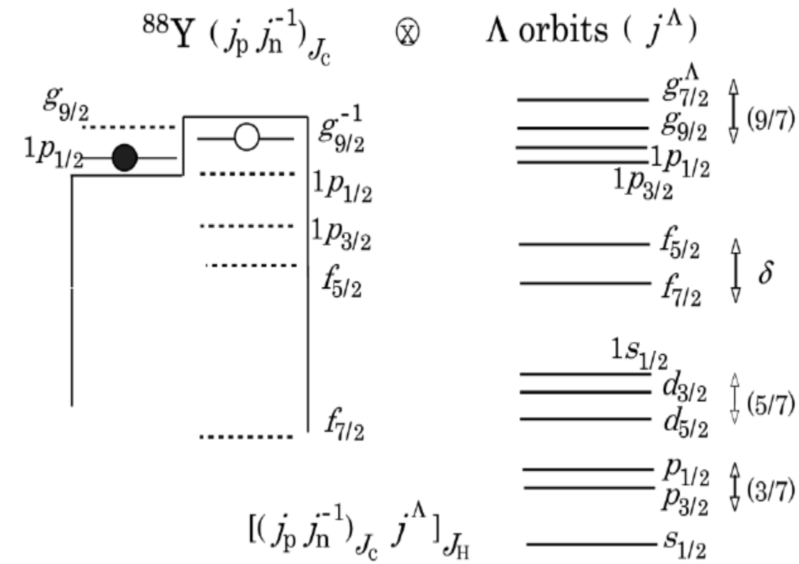


FIG. 5. Hypernuclear mass spectra of ${}_{\Lambda}^{89}$Y without (up) and wit (down) fitting curves described in the text. The quoted errors ar statistical.



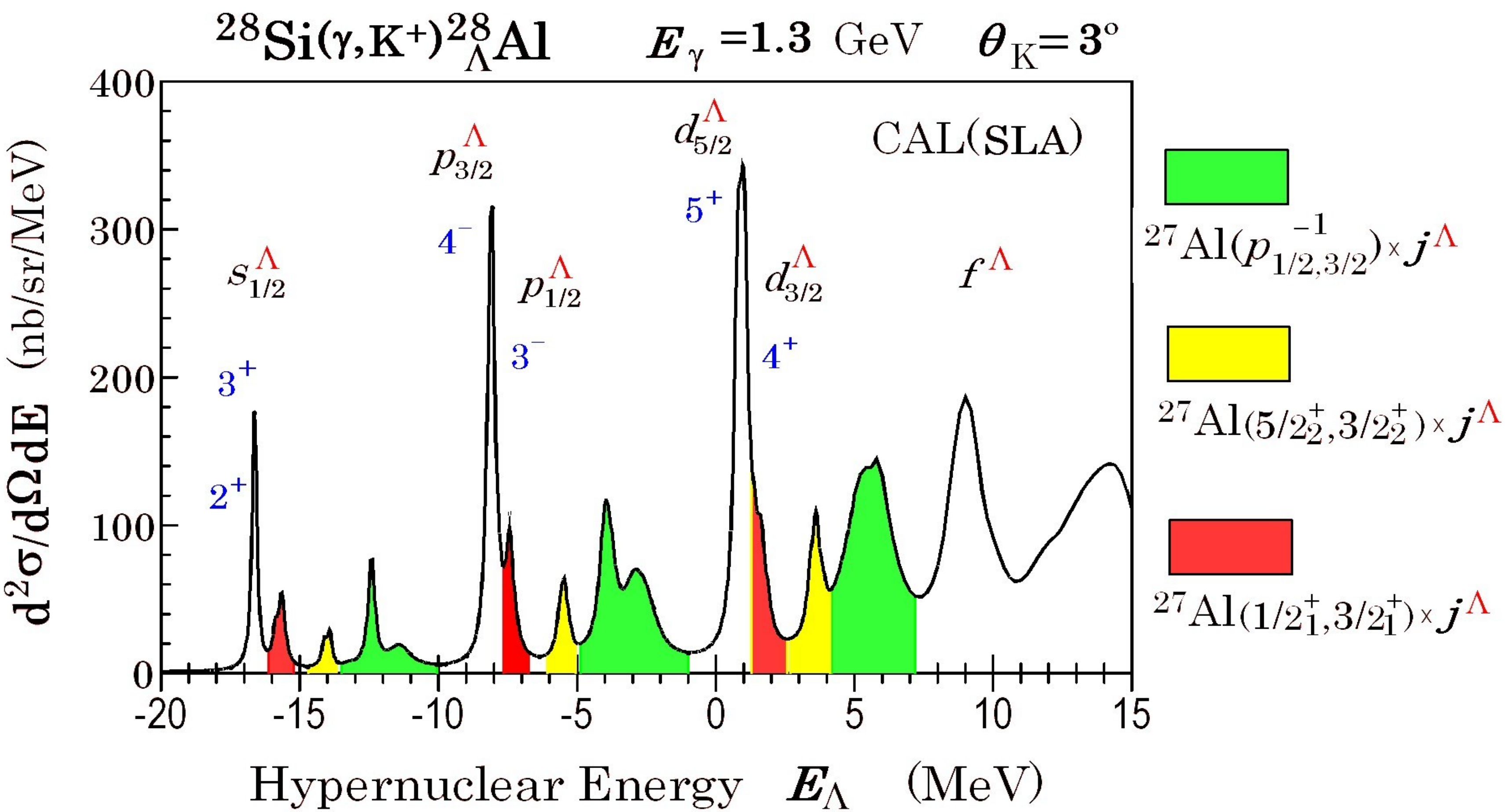


^{89}Y$(\pi^+, K^+)^{89}_{\Lambda}$Y
p_π=1.05 GeV/c
θ_K= 0
DWIA
$\delta(0f)$=0.2 MeV
2L
2R
3L
3R
$d^2\sigma/d\Omega dE$ (nb/sr/MeV)
Hypernuclear Excitation Energy E_Λ (MeV)



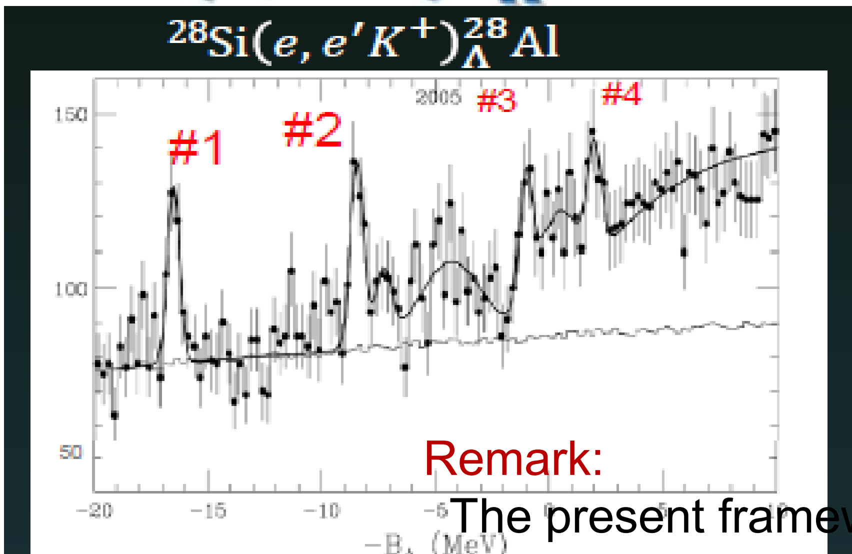
^{88}Y $(j_p\, j_n^{-1})_{J_c}$ ⊗ Λ orbits (j^Λ)
$g_{9/2}$
$1p_{1/2}$
$g_{9/2}^{-1}$
$1p_{1/2}$
$1p_{3/2}$
$f_{5/2}$
$f_{7/2}$
$[(j_p\, j_n^{-1})_{J_c}\; j^\Lambda]_{J_H}$
$g_{7/2}^\Lambda$
$g_{9/2}$
$1p_{1/2}$
$1p_{3/2}$
(9/7)δ
$f_{5/2}$
$f_{7/2}$
δ
$1s_{1/2}$
$d_{3/2}$
$d_{5/2}$
(5/7)δ
$p_{1/2}$
$p_{3/2}$
(3/7)δ
$s_{1/2}$

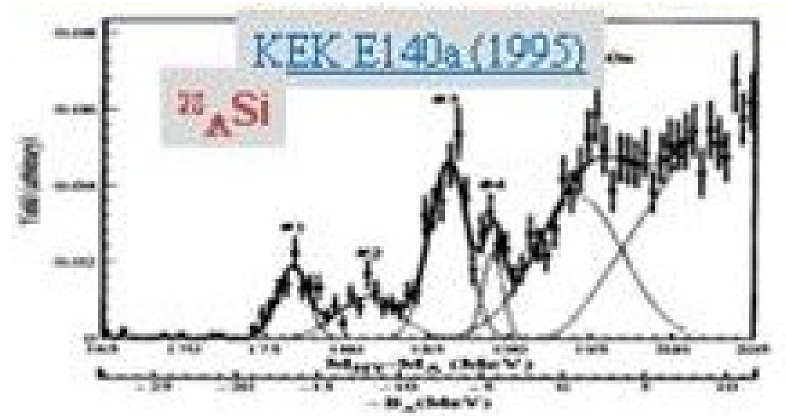
Major peaks and sub-peaks can be classified by the structure characters



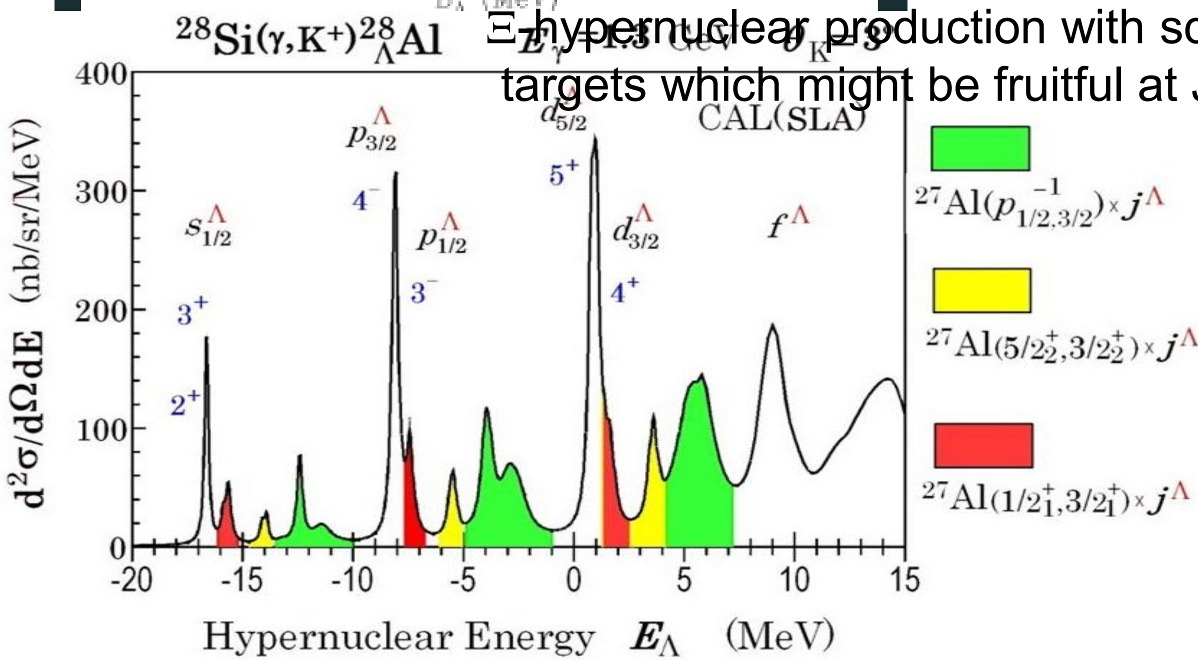
Major peak series : $[\,^{27}Al(5/2^+_1) \times j^\Lambda]_J$ with $j^\Lambda = s, p, d, \ldots$

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





Remark:
The present frameworks apply also to Ξ-hypernuclear production with sd-shell targets which might be fruitful at JPARC.

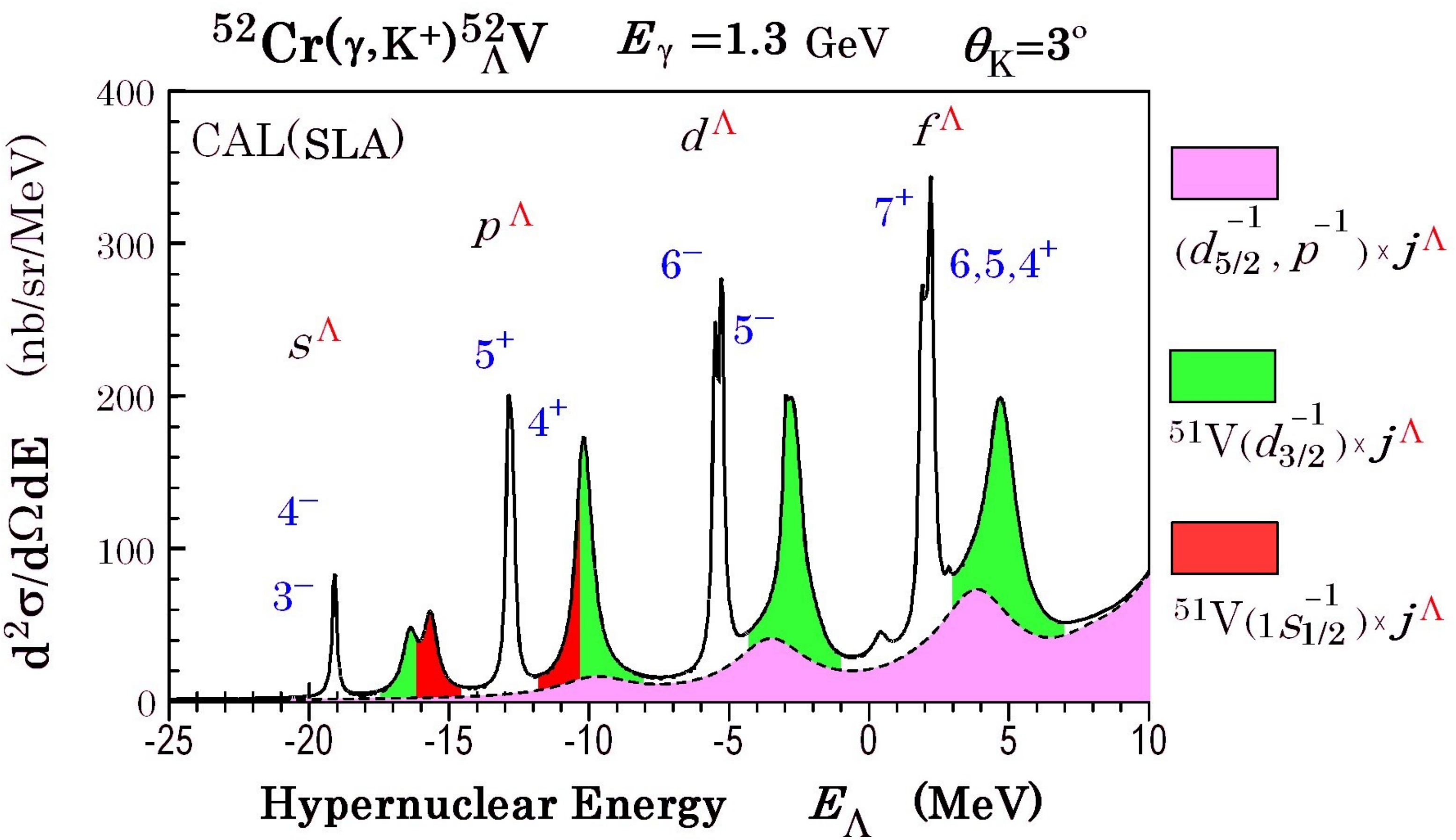


Exp. data: Nakamura(HYP2015),
Seems promising.

(waiting eagerly for finalization of exp. analysis)

^{52}Cr ($j_>$ dominant target case)

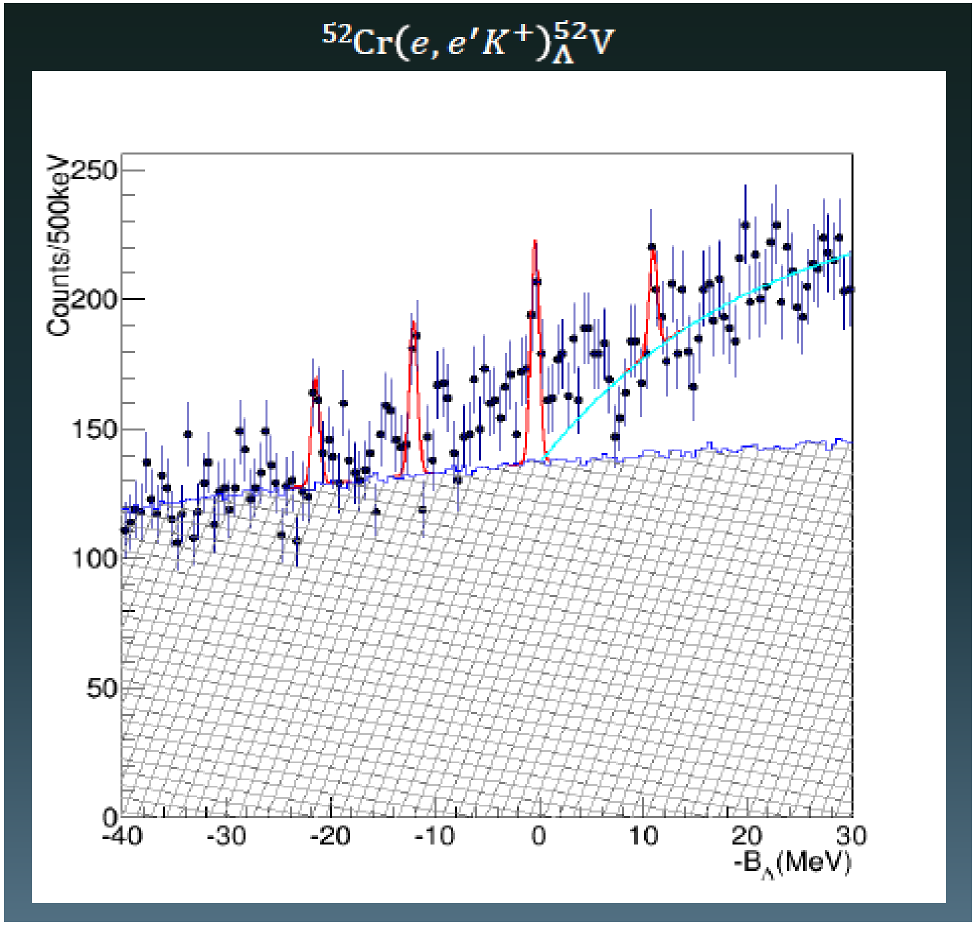
typical unnatural-parity high-spin states



Major peak series : $[\,^{51}\mathrm{V}(7/2^-;\mathrm{gs}) \times j^\Lambda]_J$ with $j^\Lambda = s, p, d, f, \ldots$

$^{52}Cr(e,e'K^+)\ ^{52}_{\Lambda}V$ in analysis

Nakamura's report. (HYP2015)



peak	B_{Λ} (MeV)
#1	-21.4
#2	-12.1
#3	-0.4
#4	+10.9

E01-115

Well-separated series of peaks

due to large *q* and spin-flip dominance:

$j_{>}=l+1/2$, $j_{<}=l-1/2$

$[(nlj)_{\mathrm{p}}^{-1}(nlj)^{\Lambda}]_J$ **a series of pronounced peaks**

***jj*- closed target** : (^{28}Si, ^{52}Cr)

$[j_{>}^{-1}\, j_{>}^{\Lambda}]_J \quad J=j_{>}+j_{>}^{\Lambda}=l_{\mathrm{p}}+l_{\Lambda}+1=L_{\mathrm{max}}+1$ (unnatural parity)

$[j_{>}^{-1}\, j_{<}^{\Lambda}]_J \quad J=j_{>}+j_{<}^{\Lambda}=l_{\mathrm{p}}+l_{\Lambda}=L_{\mathrm{max}}$ (natural parity)

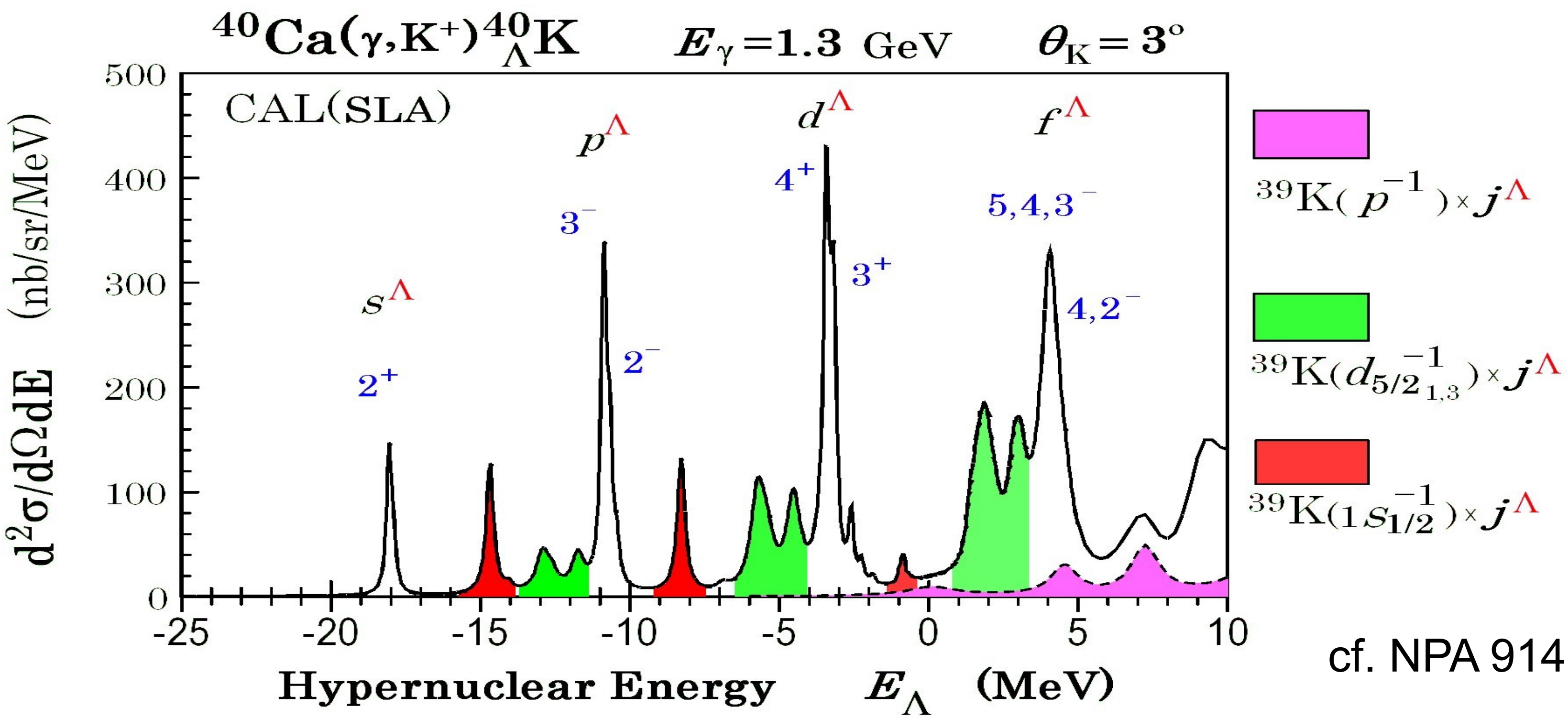
***LS*- closed target** : (^{40}Ca)

$[j_{<}^{-1}\, j_{>}^{\Lambda}]_J \quad J=j_{<}+j_{>}^{\Lambda}=l_{\mathrm{p}}+l_{\Lambda}=L_{\mathrm{max}}$ (natural parity)

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

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

the d3/2 proton-hole is responsible for the major peak series.
Focus attention to how the $_{\Lambda}^{48}$K case changes or similar to this case concerning all pronounced peaks (in progress).



cf. NPA 914(2013)

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

(4) One of the major objects is to get high presision systematics of **Λ s.p.e.**

Taken from: Millener-Dover-Gal, PRC18 (1988)

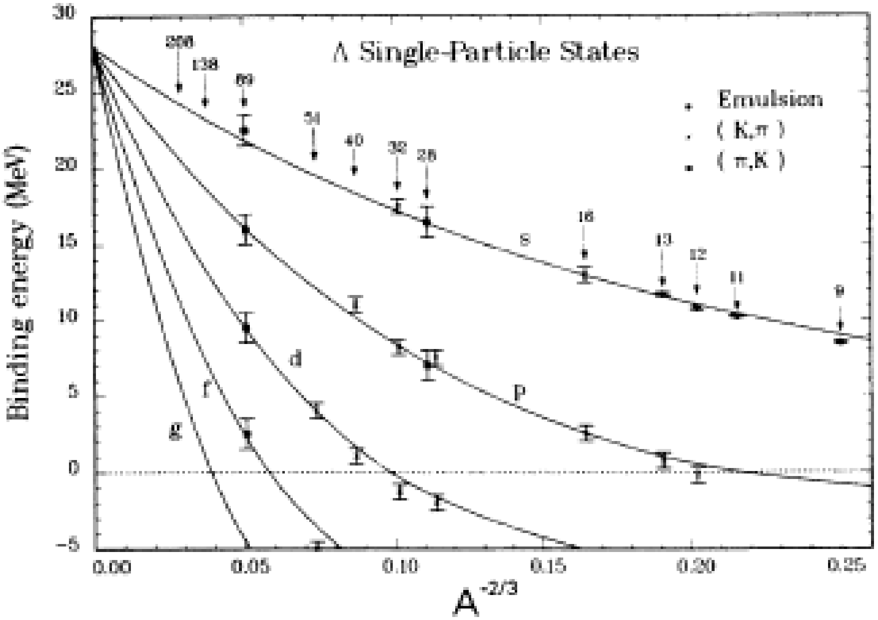


FIG. 1. The data on binding energies (B_Λ) of Λ sing

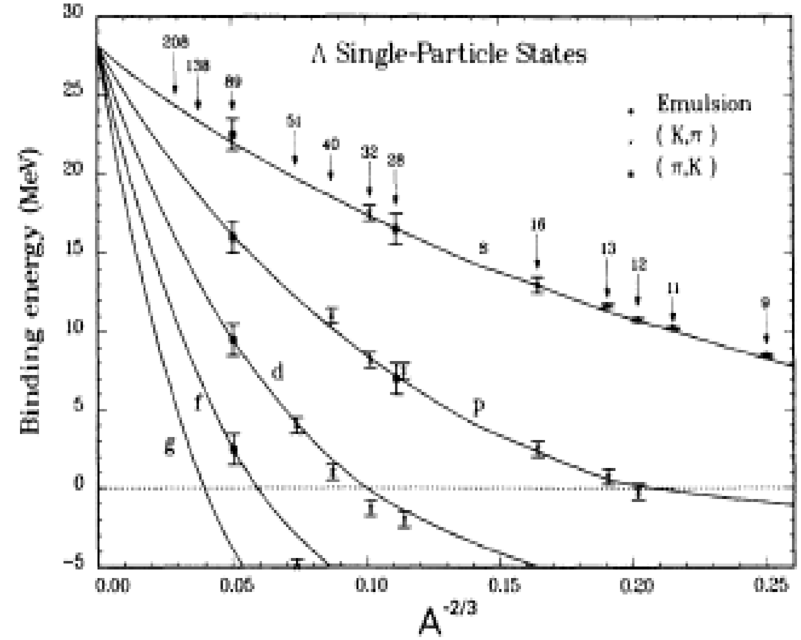


FIG. 5. Same as Fig. 4 but for the potential in Table III with $\rho^{4/3}$ density dependence.

Woods-Saxon pot. D=28MeV
r_0= 1.128+0.439A^(-2/3)

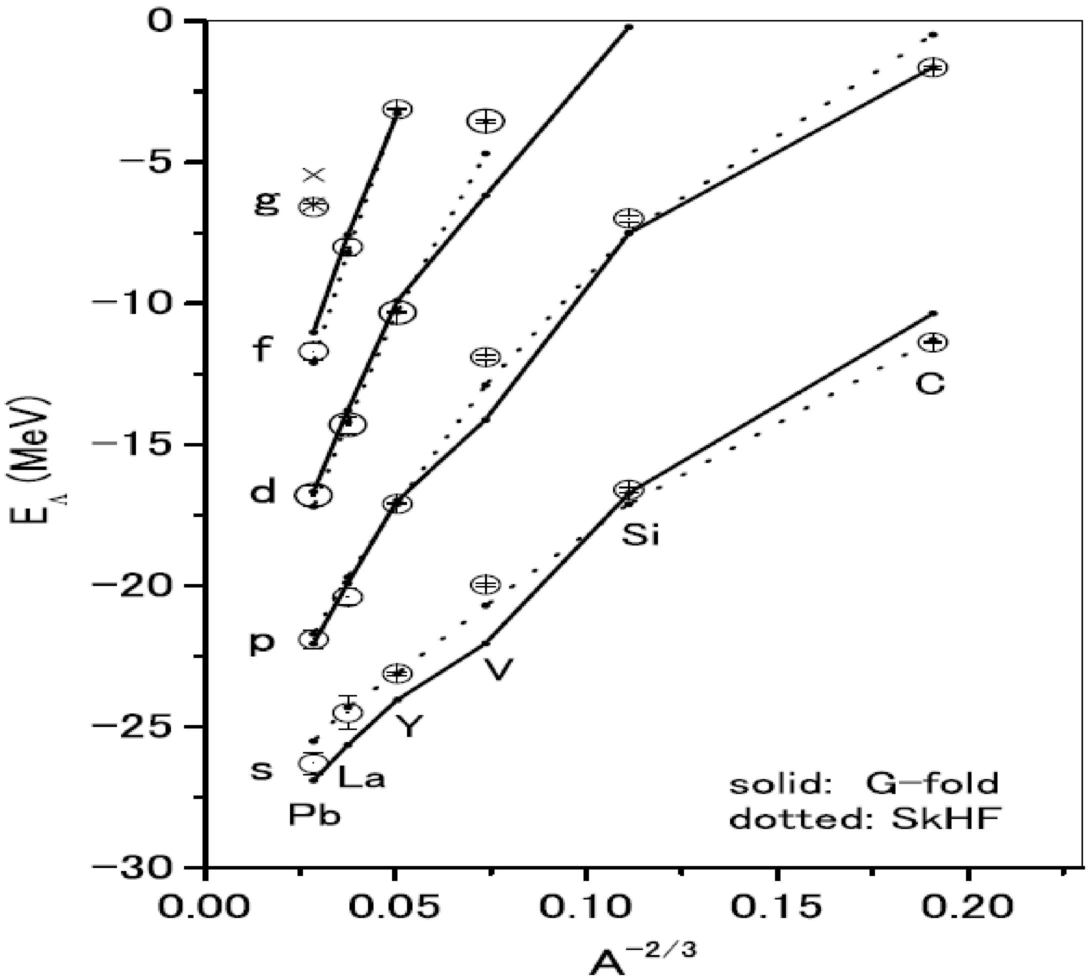
Skyrme HF with ρ^(4/3)
Density dependent

Single-particle energies of Λ

G-matrix（ESC08c） results vs. experiments

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

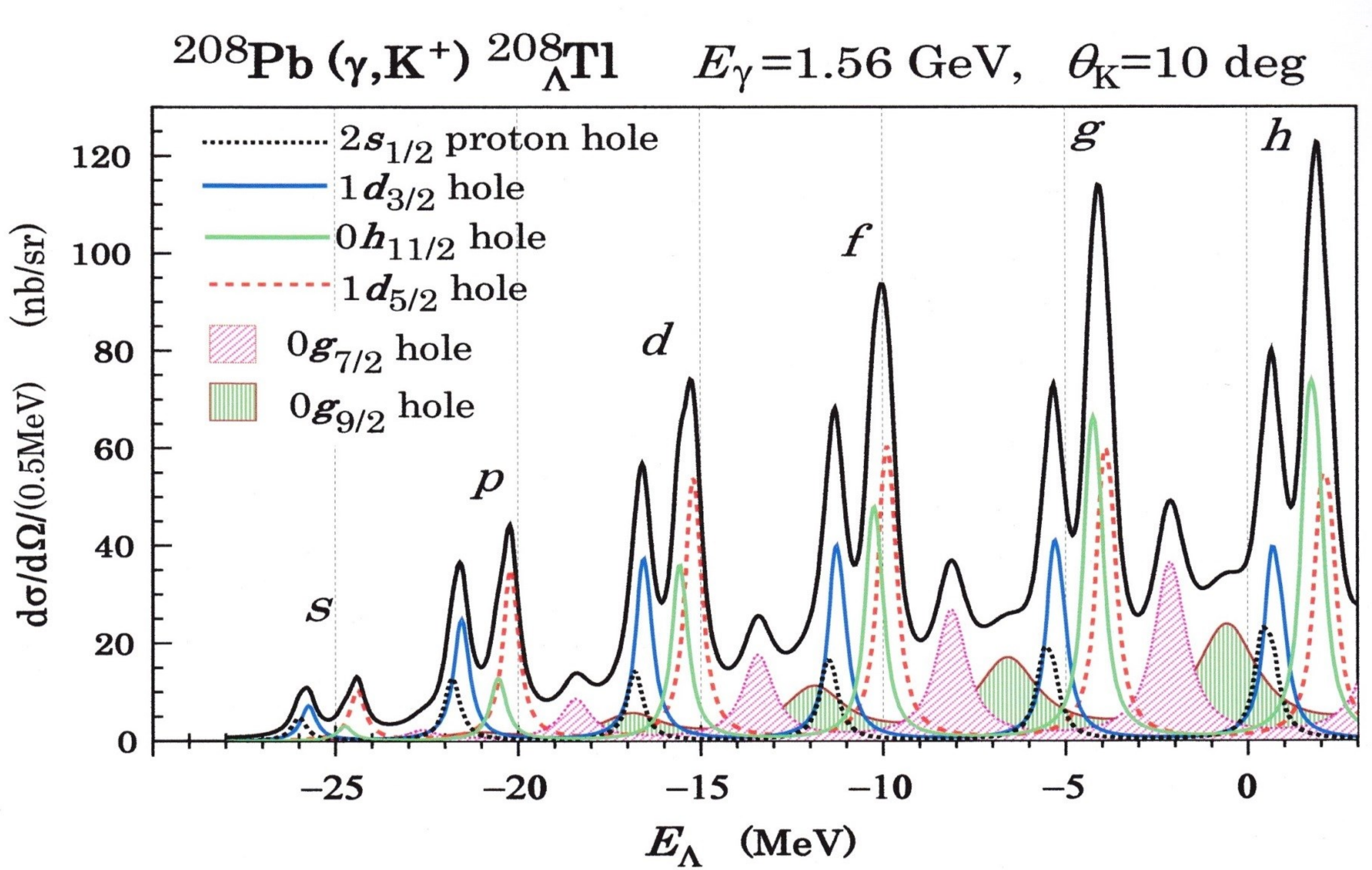
Y. Yamamoto, T. Motoba and Th. A. Rijken



High resolution exp. data @ Jlab *play a unique role.*

Combination of several *sd-, fp-* and *sdg*-shell data are important to extract systematic Λ behavior in nuclear matter.

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



Calculated with Λ (*s, p, sd, fp, sdg, fph shells*) together with core excitations.(approx. degeneracy of proton holes.

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

(5) Another interesting topics related to medium-heavy hypernuclear structure includes *Λ-rotation(deformation) coupling*

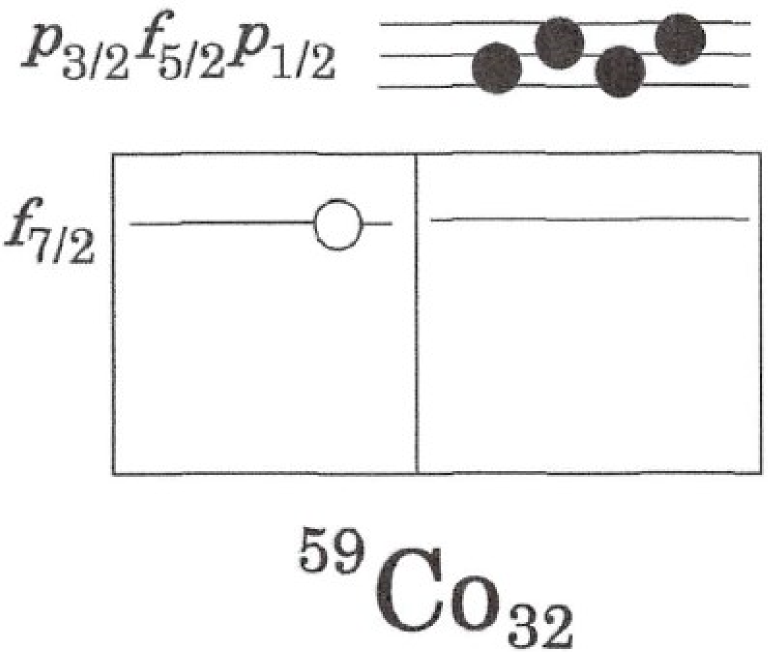
- We will get not only ‘single’ pariticle Λ states, but also sub-peaks corresponding to dynamic coupling between Λ and nuclear core.
- Among others the coupling with rotational motion is quite interesting
- Refer to Talks by Isaka and Hagino.

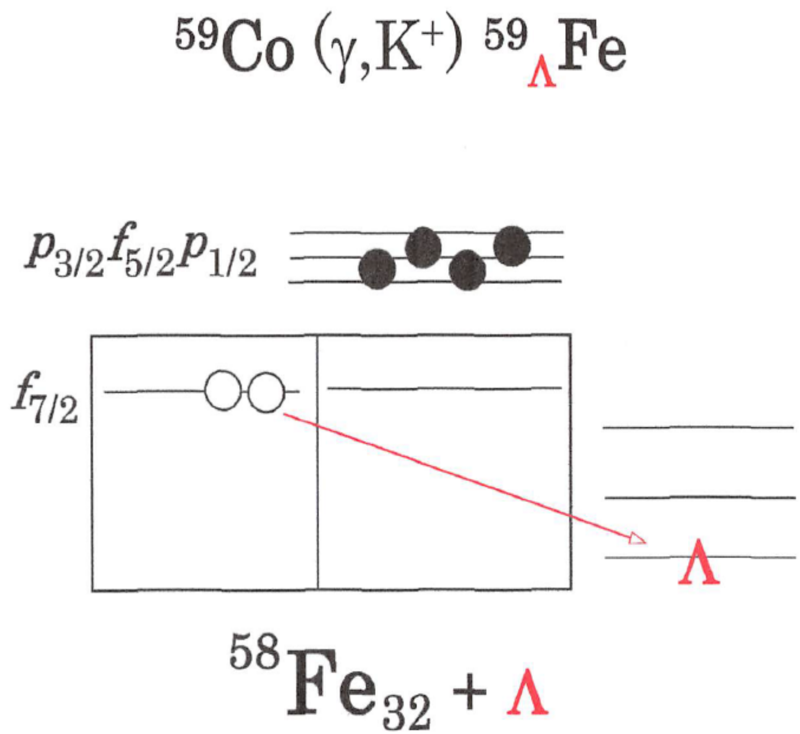
Coupling of Λ with Nuclear Rotational States

A possible way to observe it
in a *fp*-shell region by
$^{59}Co(\gamma, K^{+})\ ^{59}_{\Lambda}Fe$

Proposing another measurement of $\mu(\Lambda)$ by making use of strong internal magnetic field of **Fe**

A typical odd-Z target with $\pi(f_{7/2})^7$





3

2

2

(Stable target with 100% abundance)

"Many" protons in the large *j* @ the surface

(Private communication from Mei Hua and Hagino and preliminary results (2016) shown here)

Low-lying states of ${}^{59}_{\Lambda}$Fe with microscopic particle-rotor model

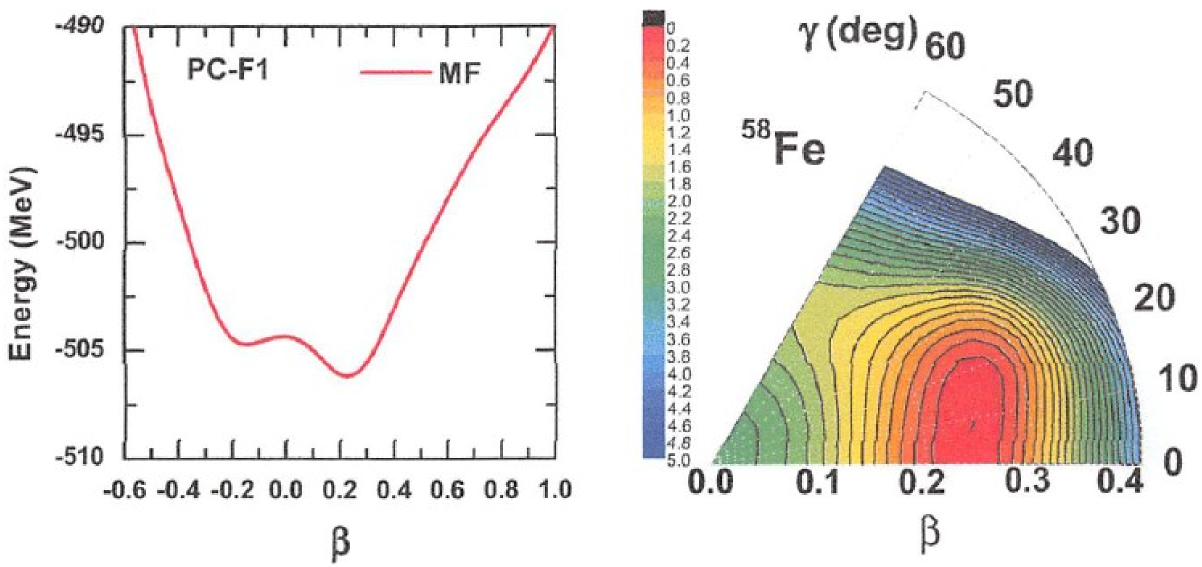
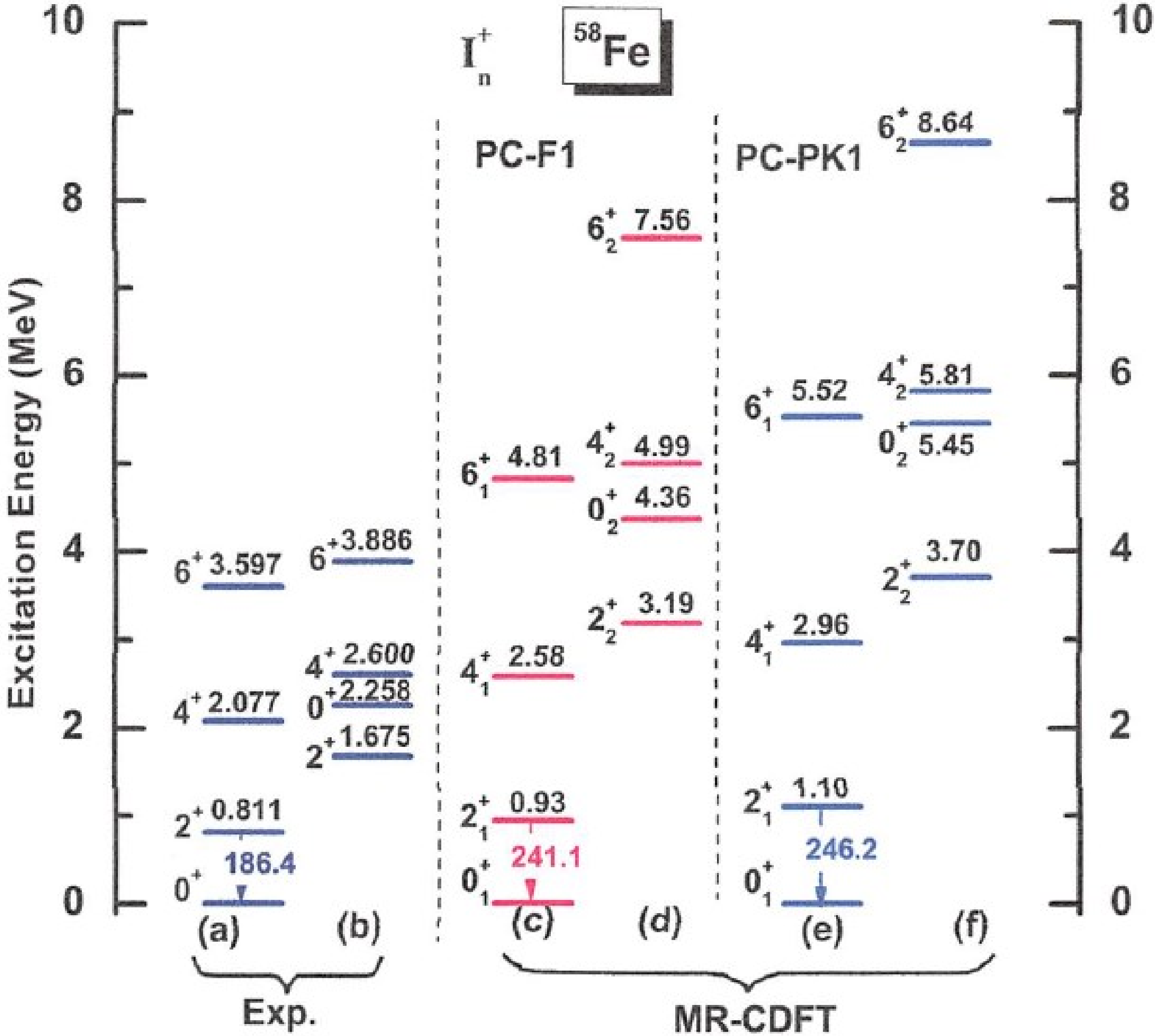


FIG. 1: The left panel:total energy of ^{58}Fe as a function of the axial deformation parameter β from constrained mean-field calculations with PC-F1 forces. The right panel:total energy of ^{58}Fe in the $\beta-\gamma$ plane. Energies are normalized to the absolute minimum.



58Fe
I^+_n
Excitation Energy (MeV)
PC-F1
PC-PK1
6+ 3.597
4+ 2.077
2+ 0.811
0+
186.4
6+ 3.886
4+ 2.600
0+ 2.258
2+ 1.675
6+1 4.81
4+1 2.58
2+1 0.93
0+1
241.1
6+2 7.56
4+2 4.99
0+2 4.36
2+2 3.19
6+1 5.52
4+1 2.96
2+1 1.10
0+1
246.2
6+2 8.64
4+2 5.81
0+2 5.45
2+2 3.70
(a)
(b)
(c)
(d)
(e)
(f)
Exp.
MR-CDFT

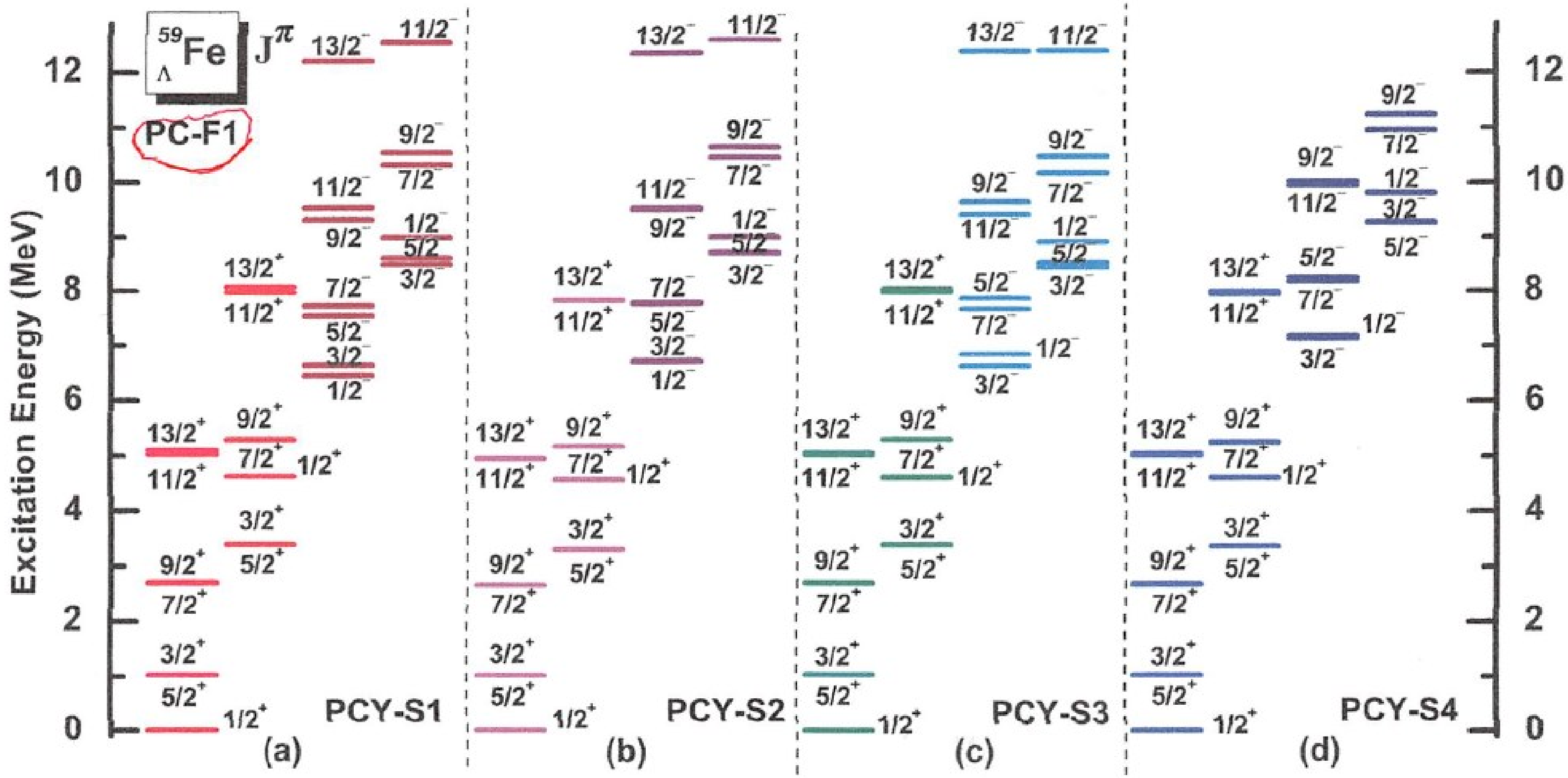
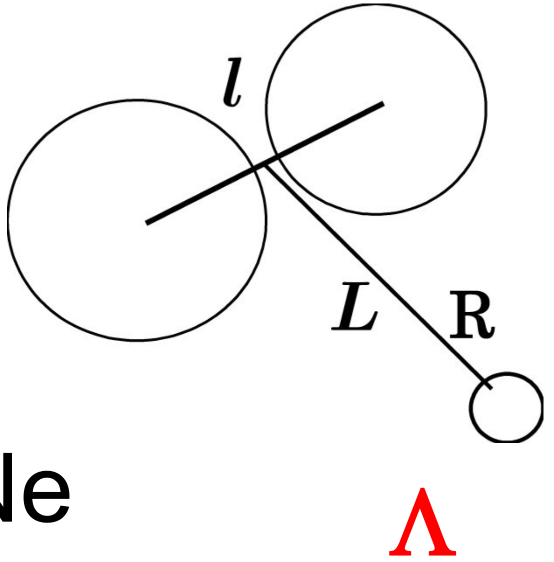


FIG. 3: The low-energy excitation spectra of $^{59}_{\Lambda}$Fe with the PC-F1 force for NN interaction and with PCY-S1(a), PCY-S2(b), PCY-S3(c) and PCY-S4(d) for ΛN interaction.

Why the strong coupling is realized between p-state Λ and α+α core ?

Schematic consideration assuming the SU(3) maximum configuration for the nuclear g.s. rotational states:



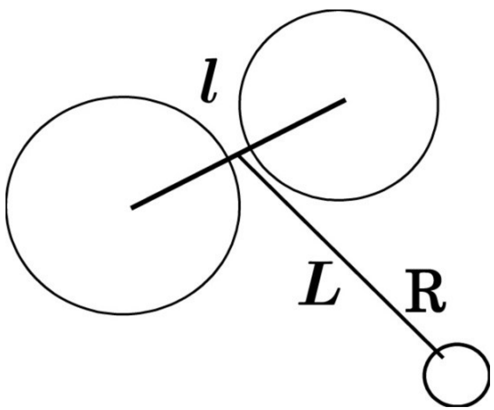
$(\lambda\mu)=(40)$ $\ell=0,2,4^+$ for ^{8}Be

$(\lambda\mu)=(04)$ $\ell=0,2,4^+$ for ^{12}C

$(\lambda\mu)=(80)$ $\ell=0,2,4,6,8^+$ for ^{20}Ne

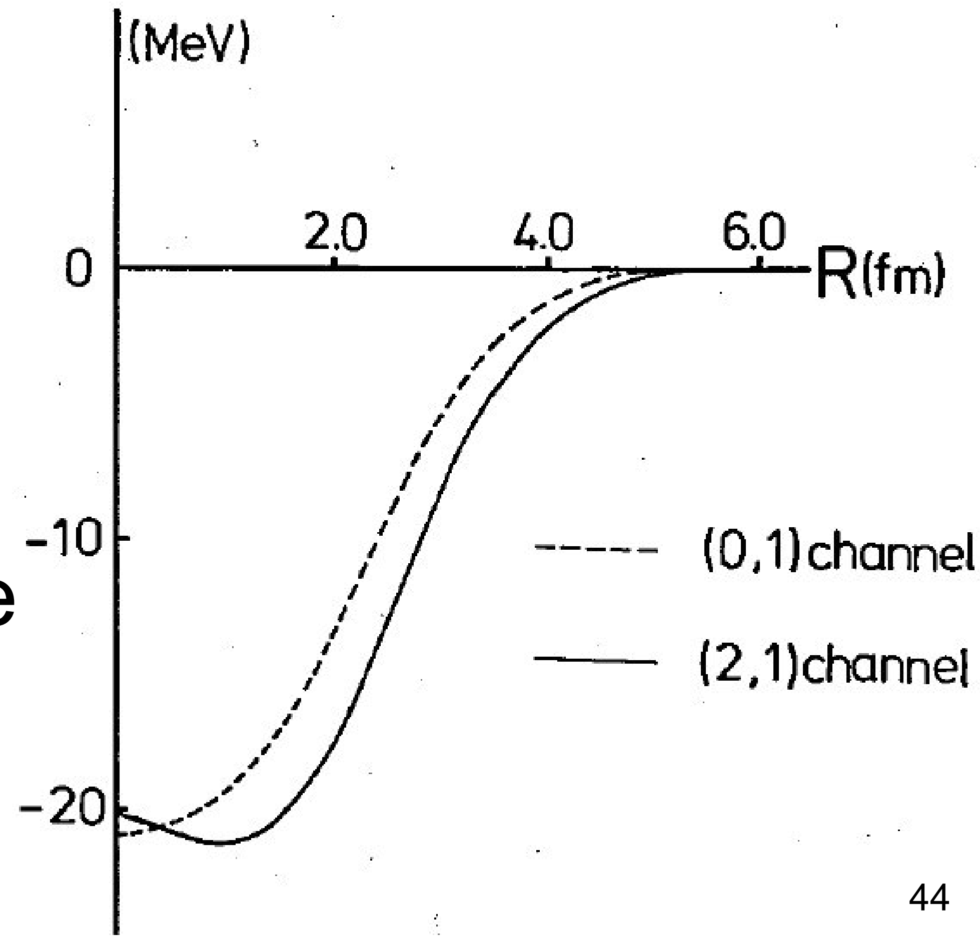
l-dependent folding potential

$$V^{J}_{lL,l'L'}(R)=\langle[\phi_l(\lambda\mu)Y_L(\hat{R})]_J|\sum_N v_{\Lambda N}|[\phi_{l'}(\lambda\mu)Y_{L'}(\hat{R})]_J\rangle$$



Diagonal potential

$V_{lL}(R)$ for Λ p-state

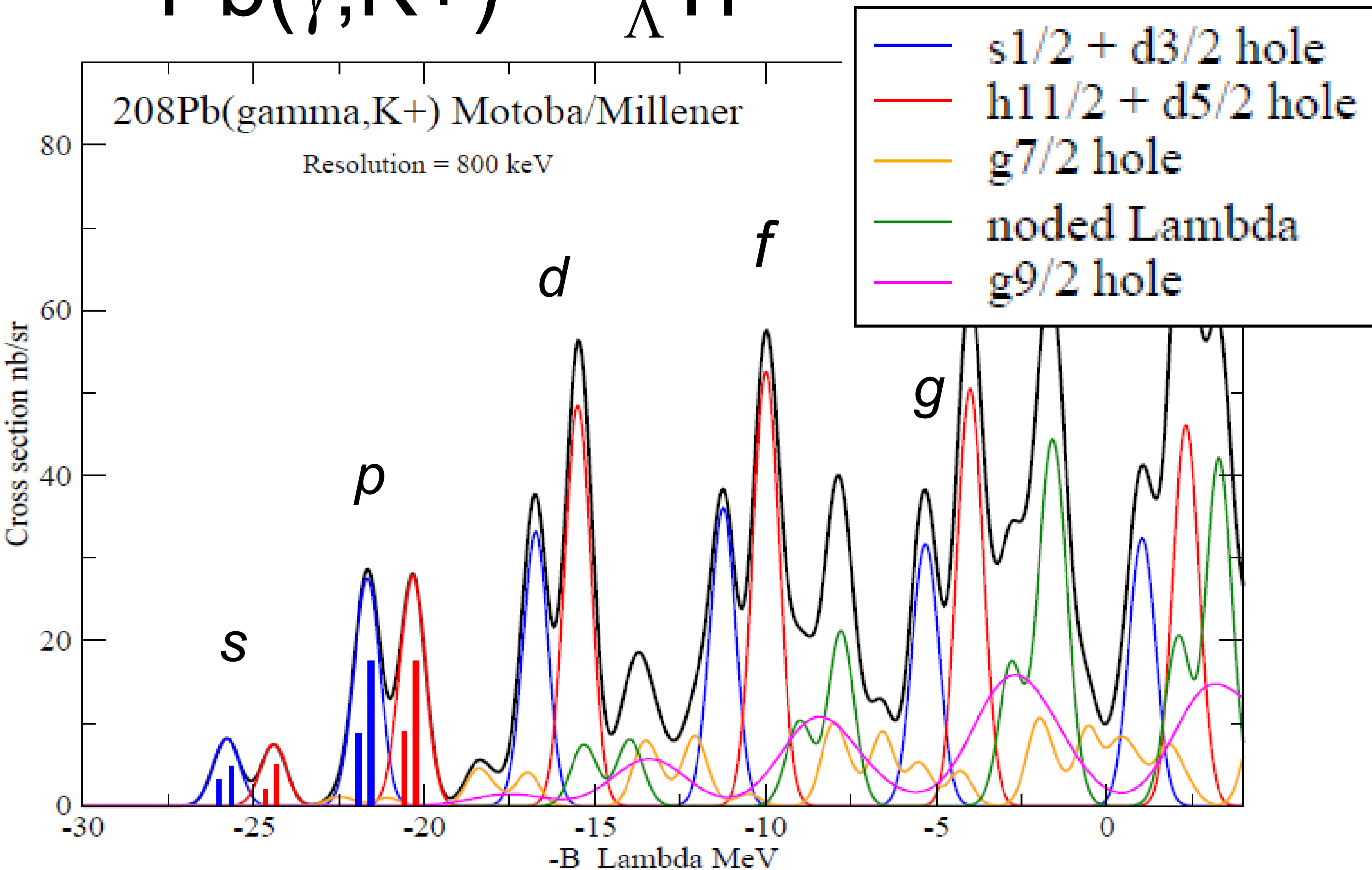


l=2 is more attractive than l=0.

Summary and outlook

1) Based on the (γ,K+) reaction characteristics, typical physics contents are discussed by showing theoretical production cross section spectra.
2) Among others the DWIA predictions for p-shell, ${}^{28}_{\Lambda}$Al and ^{52}Cr are well compared with the recent expts. ^{40}Ca and ^{208}Pb are also demonstrated.
3) In addition to the Λ s.p.e., the dynamical coupling of Λ with collective nuclear rotation is emphasized.
4) New feature of "parity-mixing" mediated by hyperon has been pointed out, and the detailed calculation is in progress. This can be also applied to heavier Hy.

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



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