Photoproduction of typical hypernuclei

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(1) Characteristics utilized in ^{4}He(γ,K^{+})

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

(5) Λ-rotation(deformation) coupling

(6) Summary

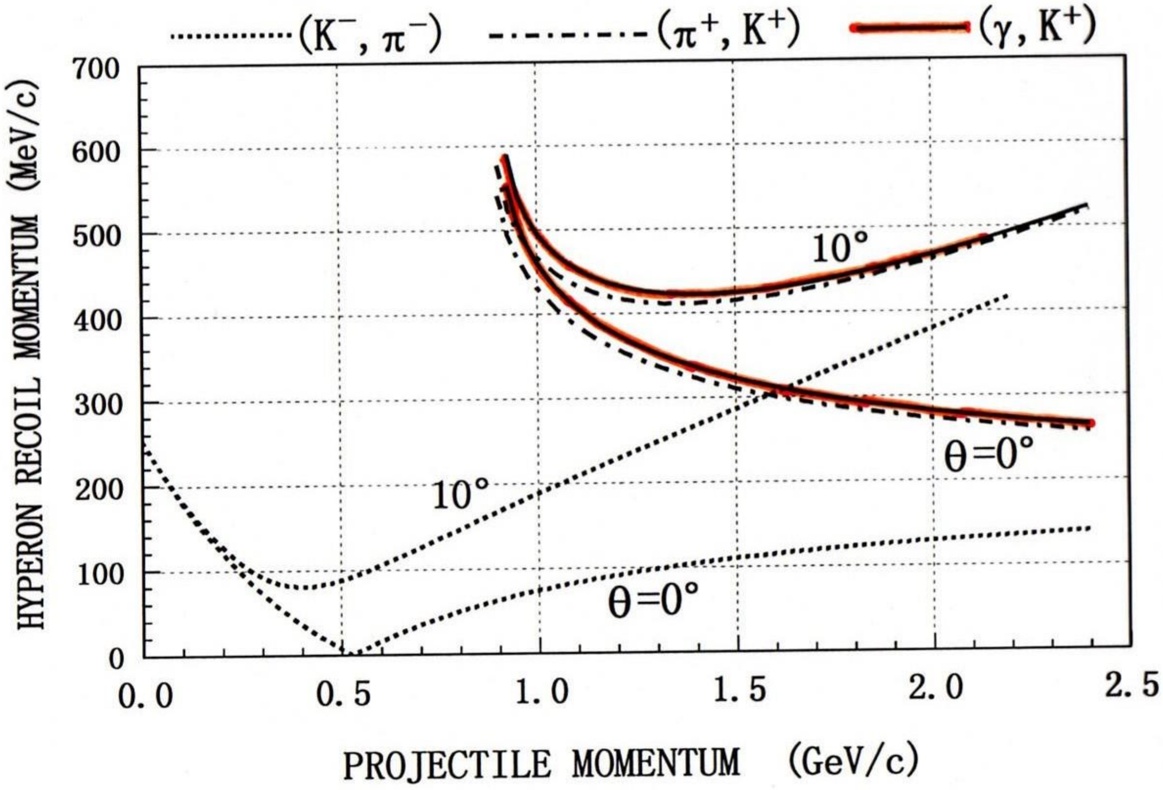
(0) **BASICS:** Hyperon **recoil momentum** and the **transition operator itself** determine the reaction characteristics

(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

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

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

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

(π,K) case

(2) Elementary amplitude N → Y

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

Lab $d\sigma/d\Omega$ photoproduction case (2Lab)

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

$$\langle \boldsymbol{k}-\boldsymbol{p},\,\boldsymbol{p}|t|\boldsymbol{k},0\rangle_L=a_1(\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon})+a_2(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}})(\hat{\boldsymbol{p}}\cdot\boldsymbol{\epsilon})+a_3(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{p}})(\hat{\boldsymbol{p}}\cdot\boldsymbol{\epsilon})+a_4\{(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{p}})\cdot\boldsymbol{\epsilon}\}\,. \tag{2·5}$$

spin non-flip term

$$\langle \boldsymbol{k}-\boldsymbol{p},\,\boldsymbol{p}|t|\boldsymbol{k},0\rangle_L=\epsilon_0(f_0+g_0\sigma_0)+\epsilon_x(g_1\sigma_1+g_{-1}\sigma_{-1}) \tag{2·11}$$

spin-flip terms

with definitions of the coefficients:

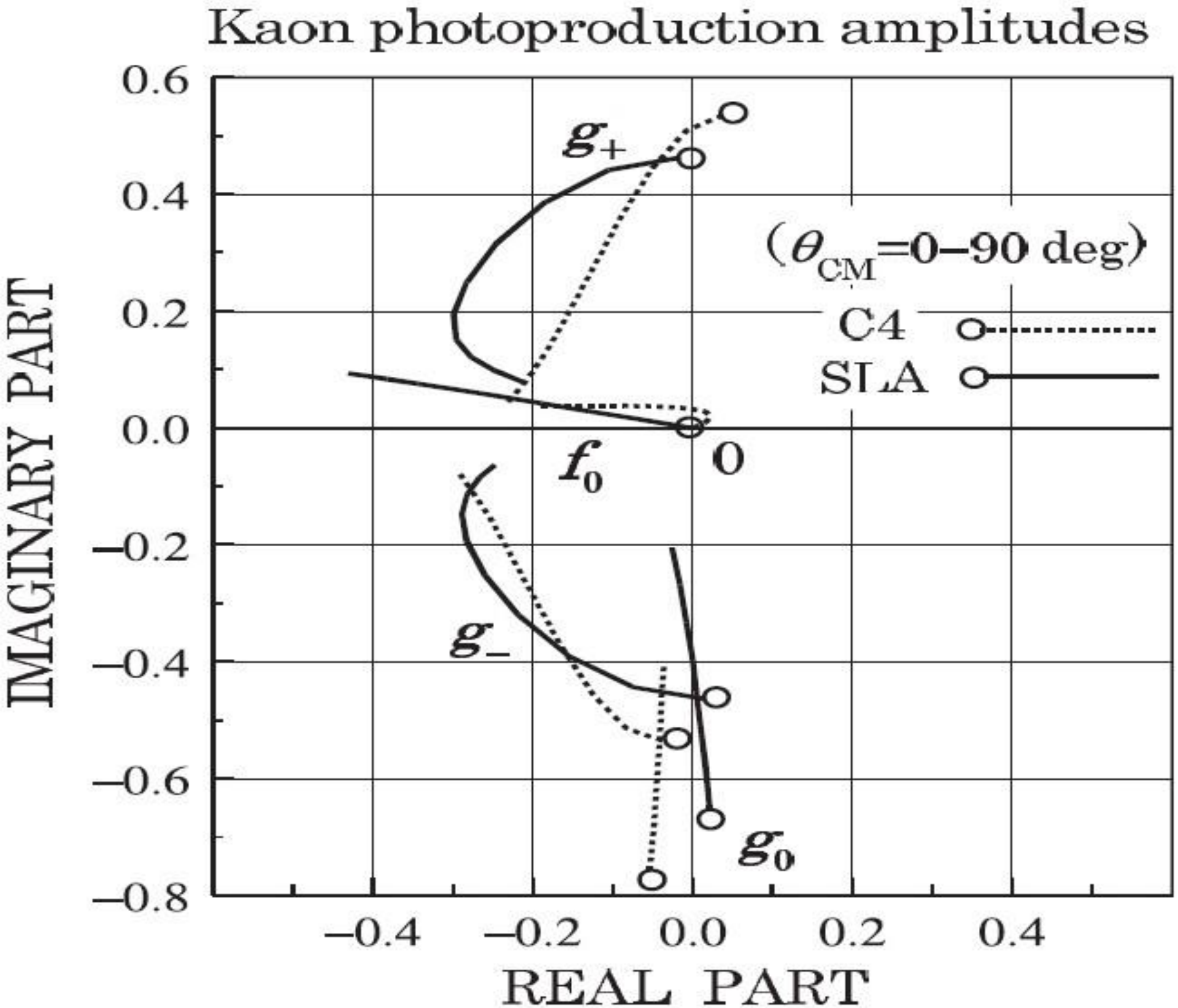
$$f_0=a_4\sin\theta_L\,,$$

$$g_0=a_1\,,$$

$$g_{\pm1}=\frac{1}{\sqrt{2}}\{\mp(a_1+a_3\sin^2\theta_L)-i\sin\theta_L(a_2+a_3\cos\theta_L)\}\,. \tag{2·12}$$

(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

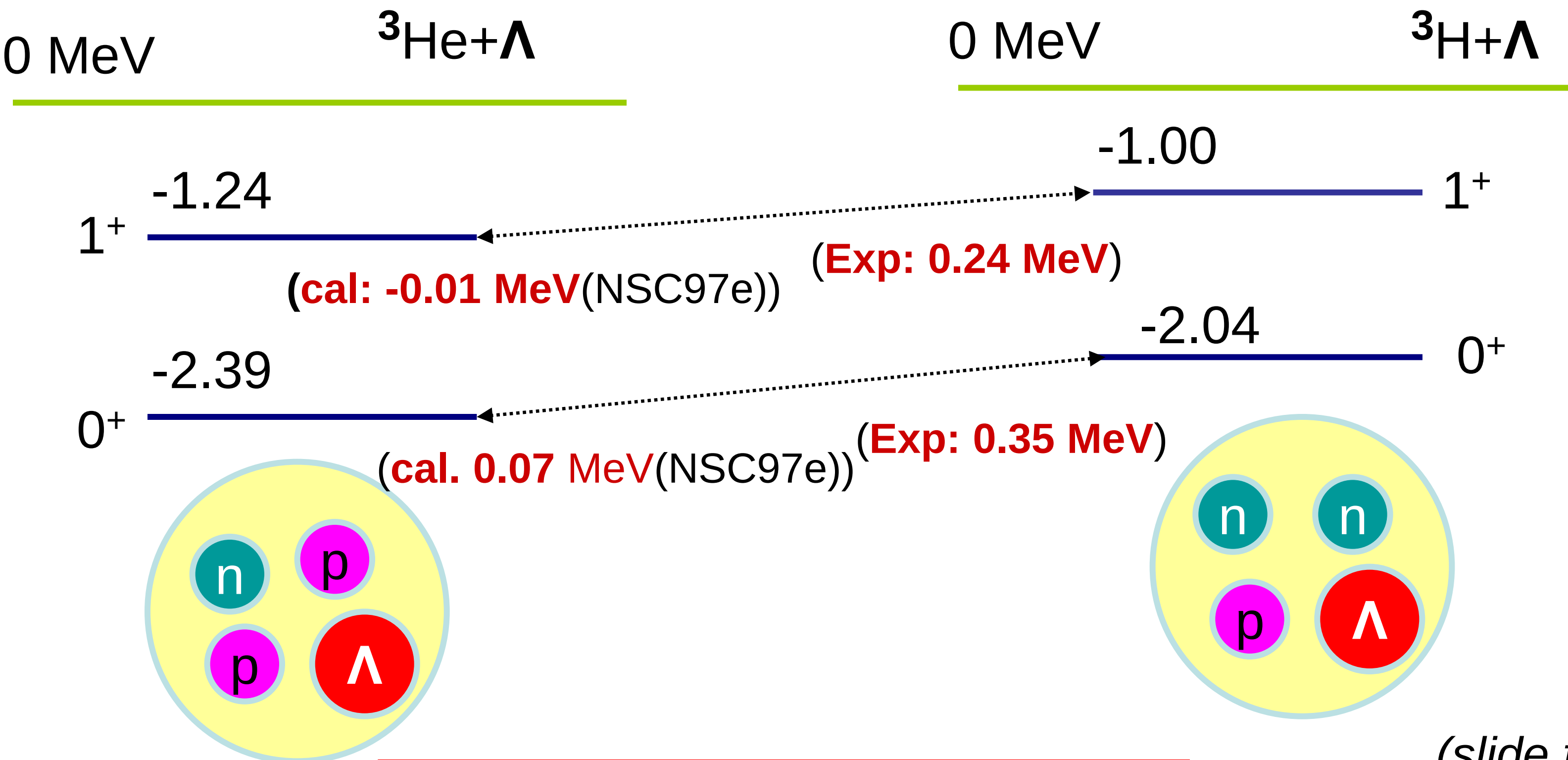
(A proposal from theory side)

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.)

Many 4-body calculations have been done → Talks by Hiyama, Gal



$^4_\Lambda$He

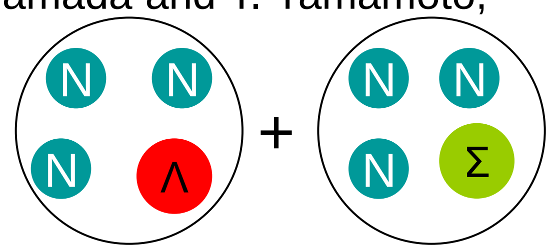
$^4_\Lambda$H

(slide from Hiyama)

- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

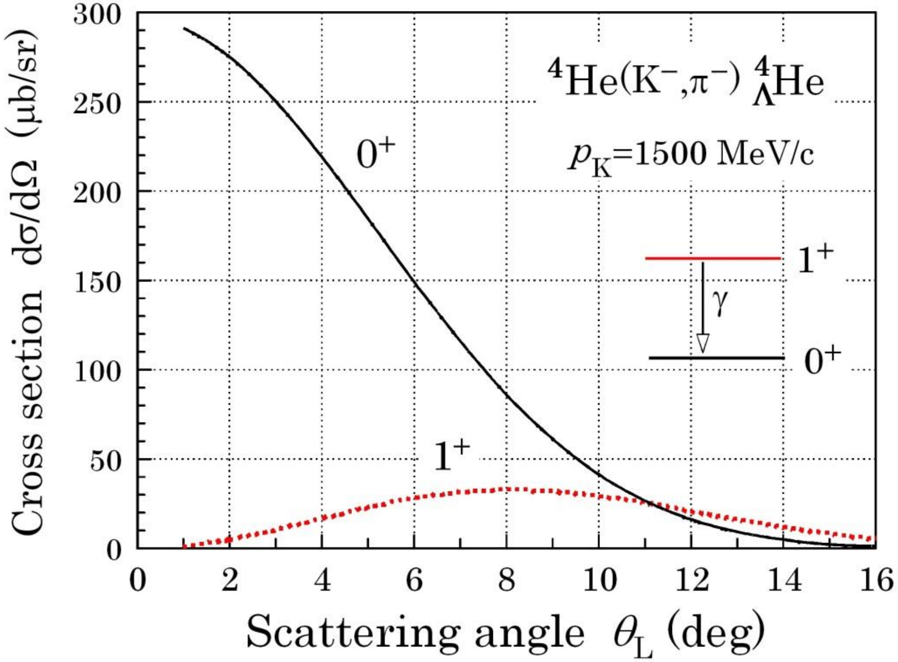
- E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. C65, 011301(R) (2001).

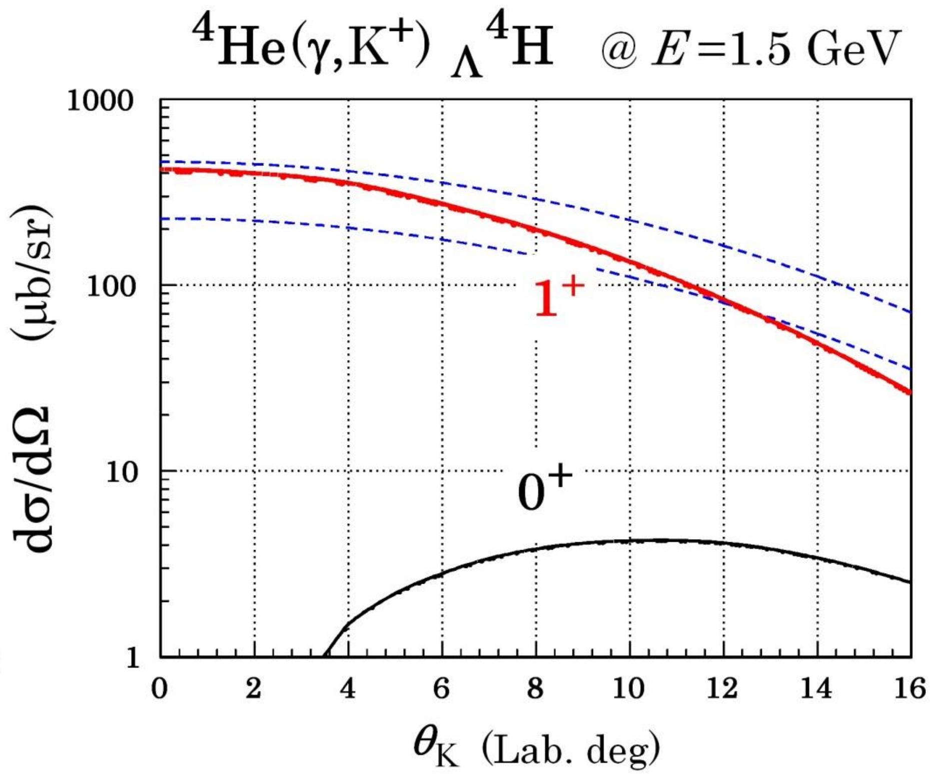
- H. Nemura. Y. Akaishi and Y. Suzuki, Phys. Rev. Lett.89, 142504 (2002).



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

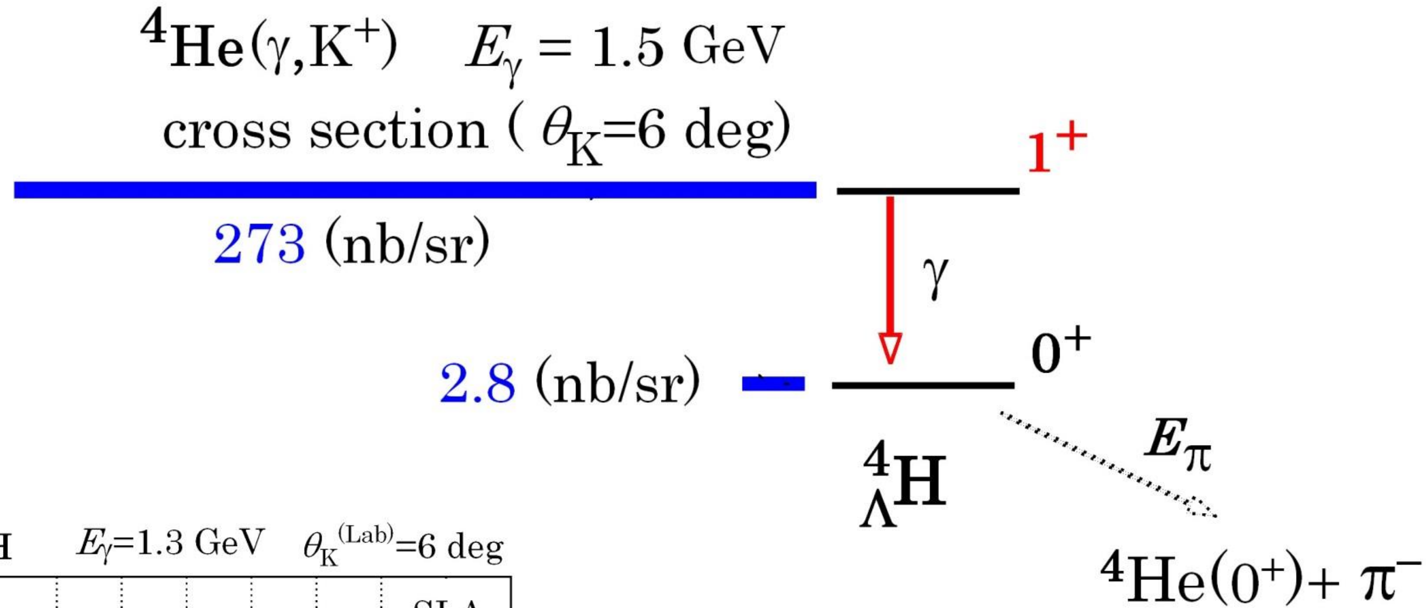
(A reaction theoretical view)

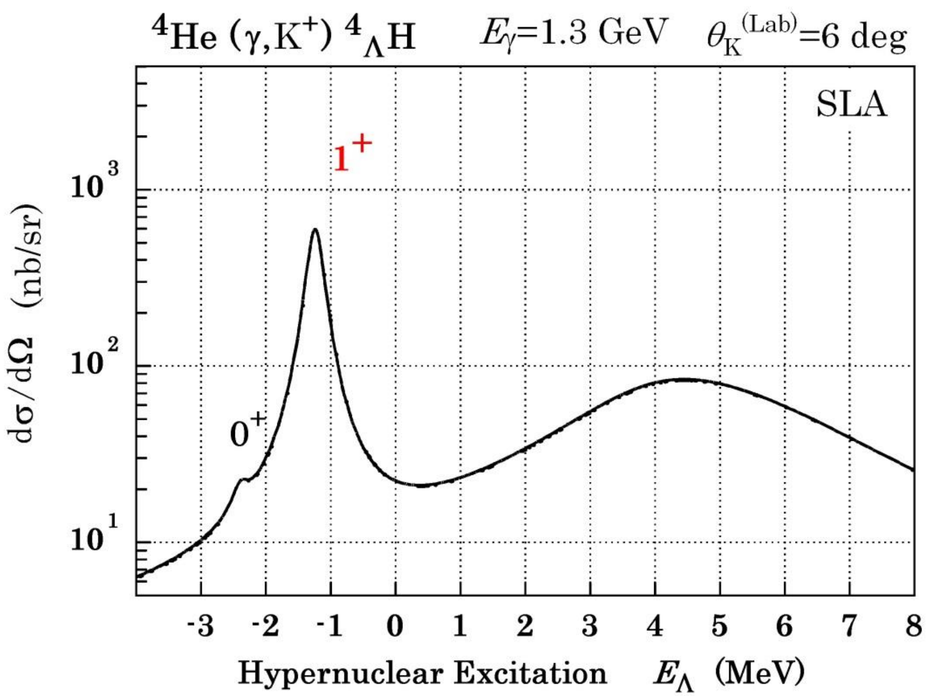




1^+ gets minor X-S but excited anyway, then (K,πγ) coincidence method successful. → Tamura's talk

X-S(1+) is predominantly Larger than X-S(0+)





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

E(1+) peak energy will be determined by $^4He(e,e'K^+)$

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

- Success of JLab experiments (Hall A & C) on p-shell targets ---- high E resolution ~540keV
- Suggesting new theoretical aspects

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

Tang et al. PRC 90(2014)

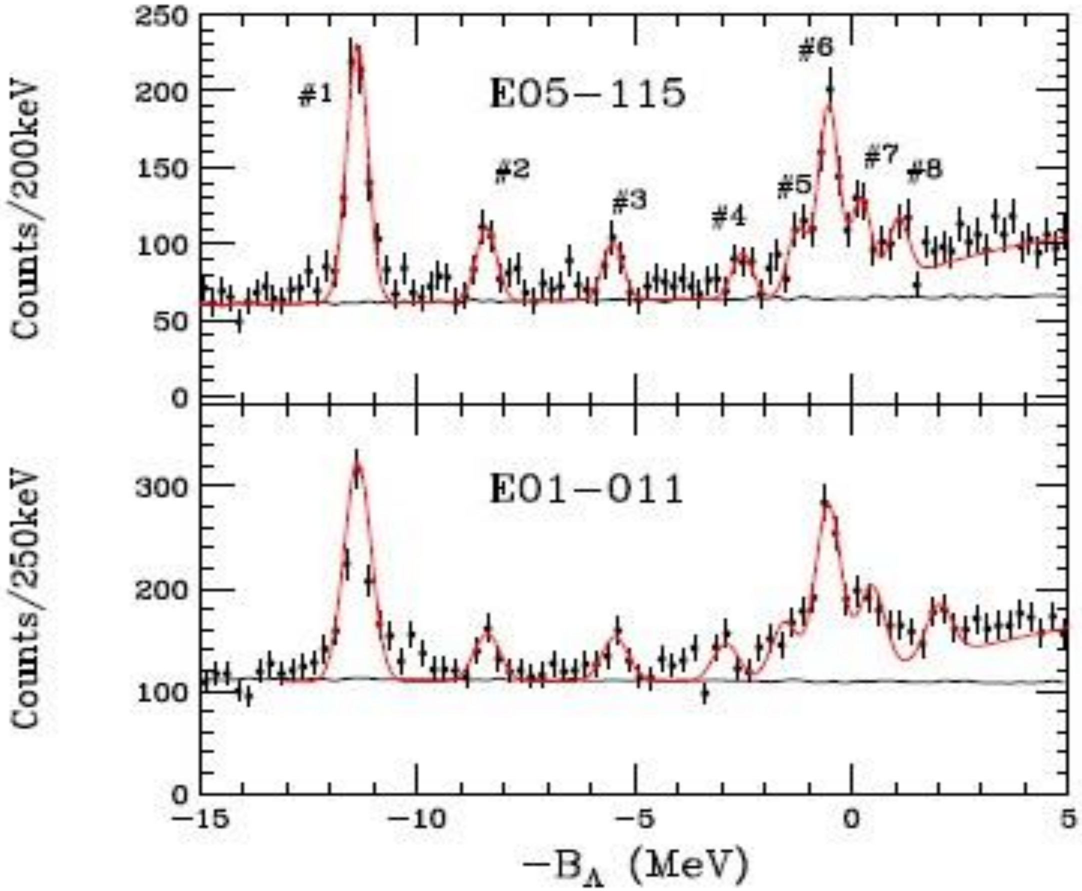
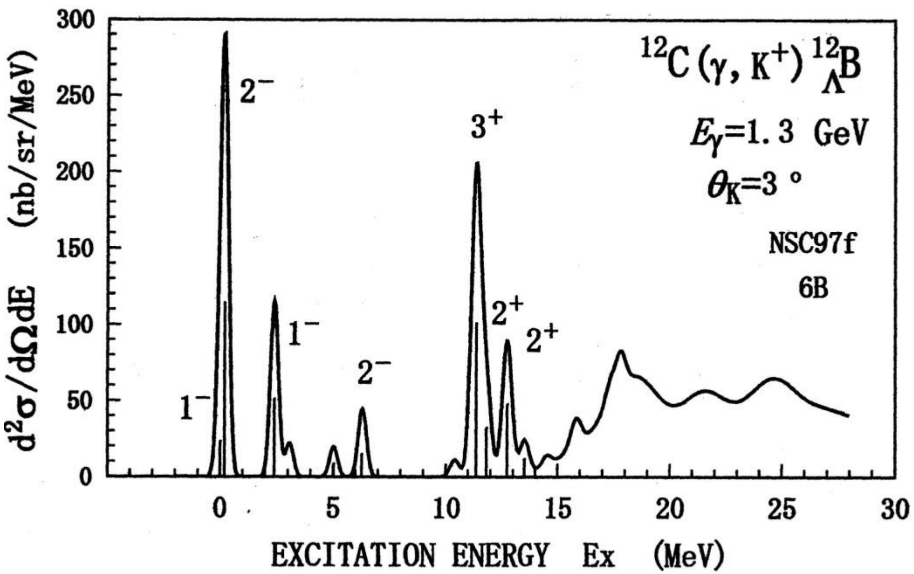
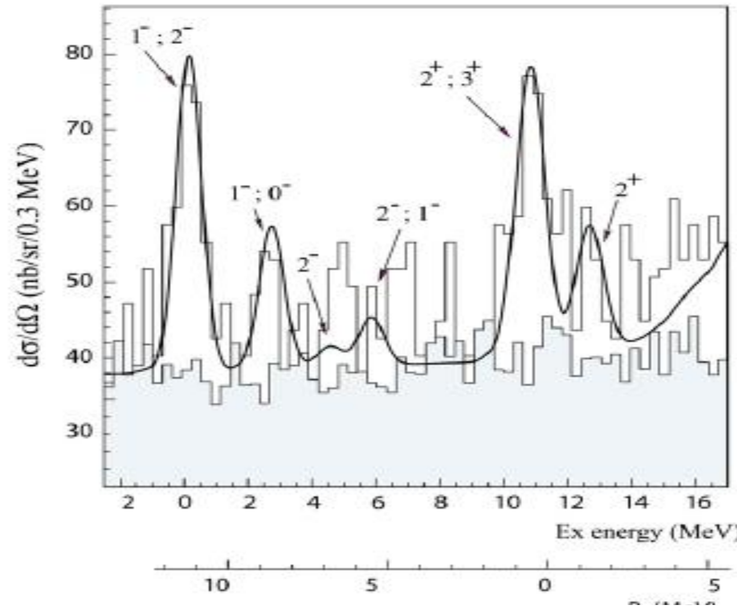


FIG. 10. (Color online) Spectroscopy of $^{12}_{\Lambda}B$ from the E05-115 and E01-011 experiments. The area below the black line is the accidental background.

Theor. prediction vs. (e,e'K$^+$) experiments

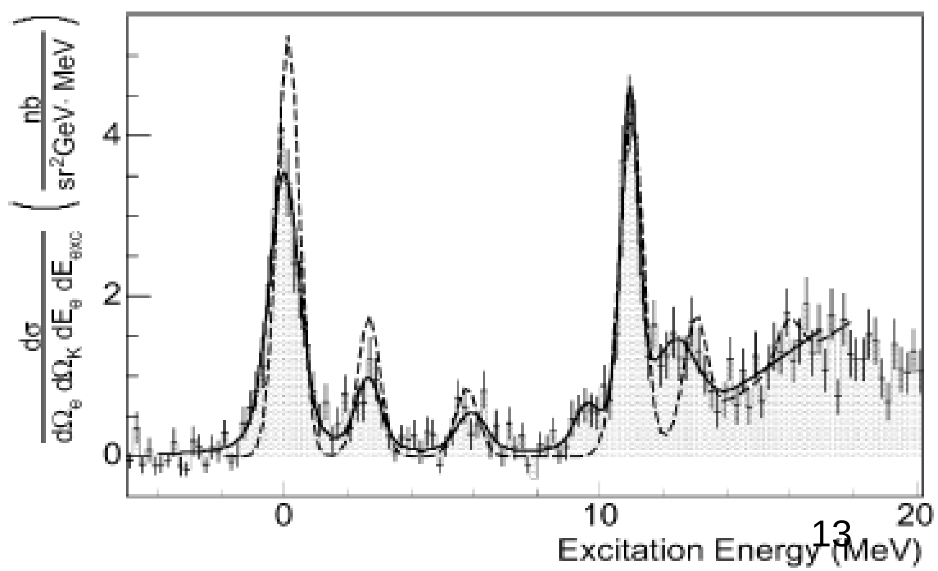




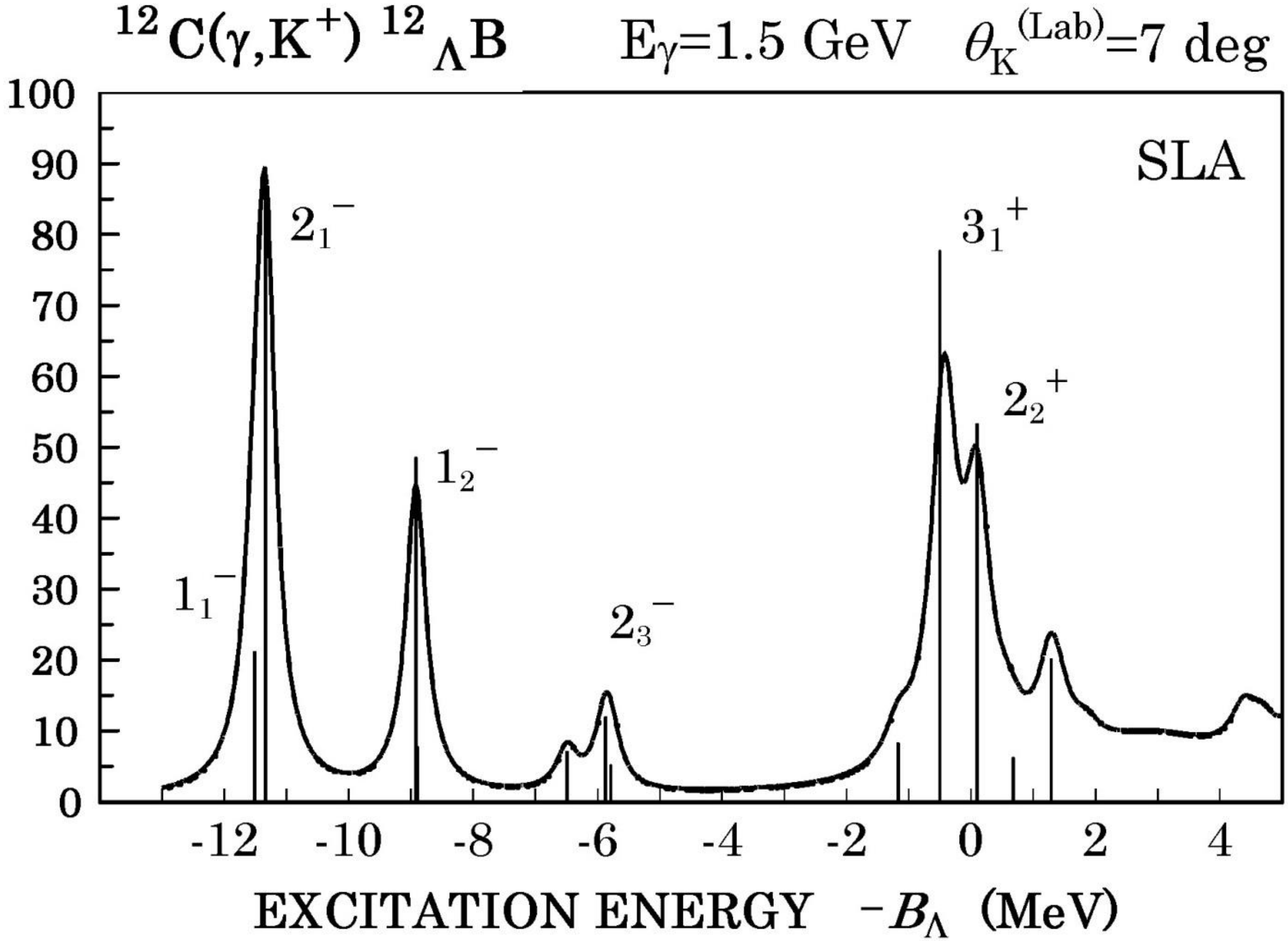
Motoba. Sotona, Itonaga,
Prog.Theor.Phys.Sup.**117** (**1994**)
T.M. *Mesons & Light Nuclei* (2000)
updated w/NSC97f.

---→

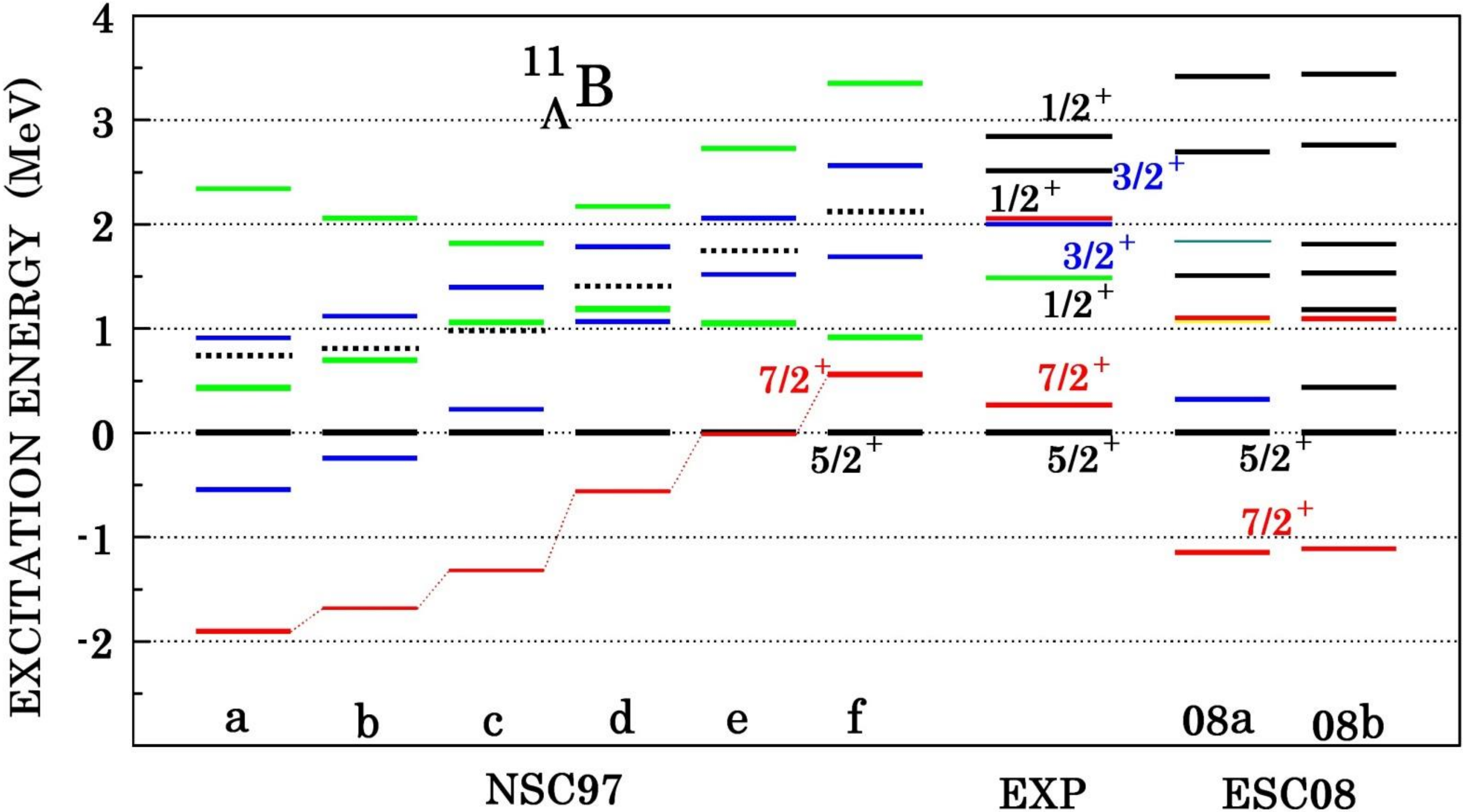
Hall C (up) T. Miyoshi et al.
*P.R.L.***90** (2003) 232502. **Γ=0.75keV**
Hall A (bottom), J.J. LeRose et al.
N.P. A**804** (2008) 116. **Γ=0.67keV**



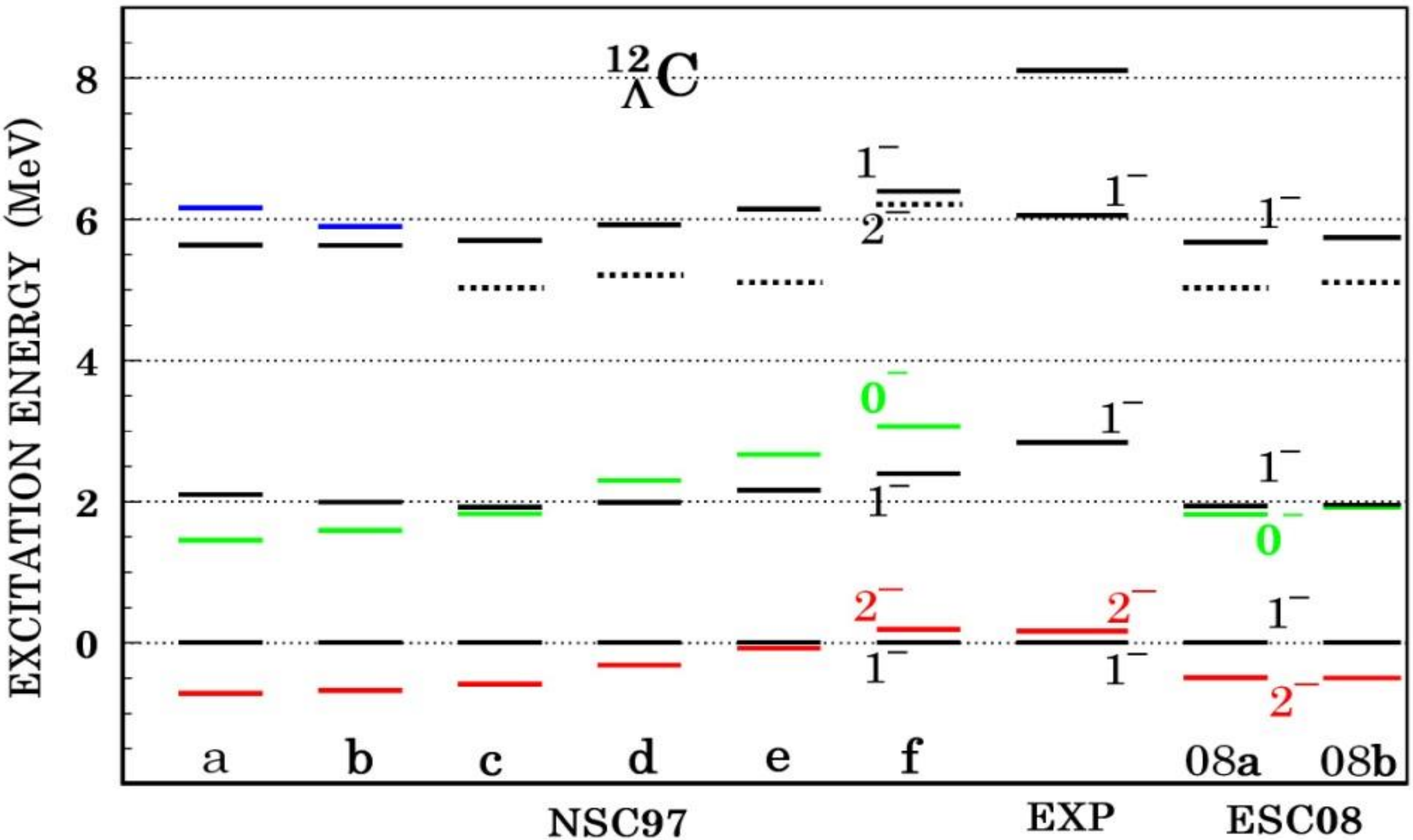
DWIA calculation



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



Providing discrimination of several versions of meson theoretical Y-N interaction models



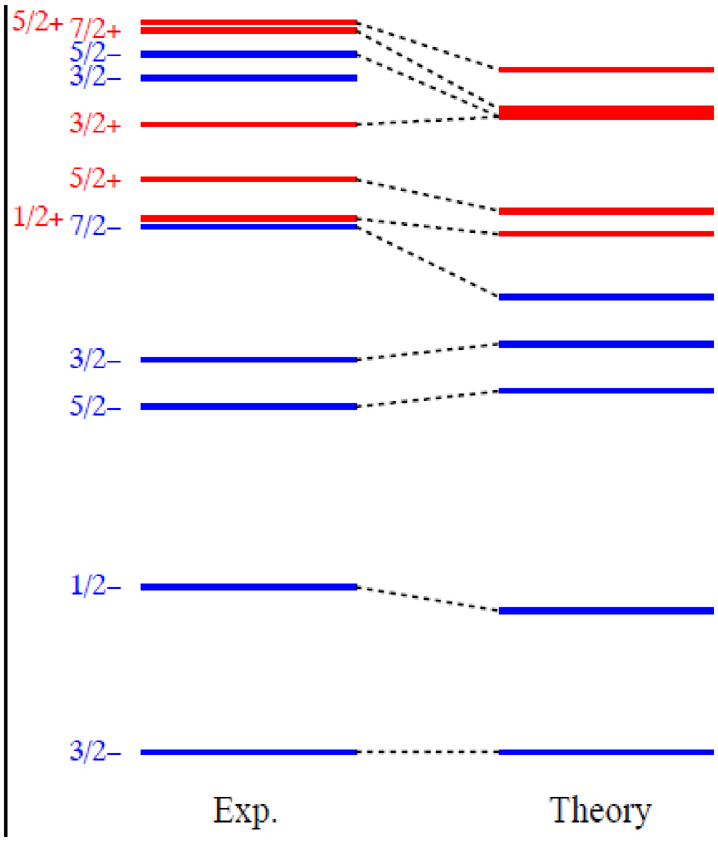
EXP. X-S and DWIA estimates are in good correspondence

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

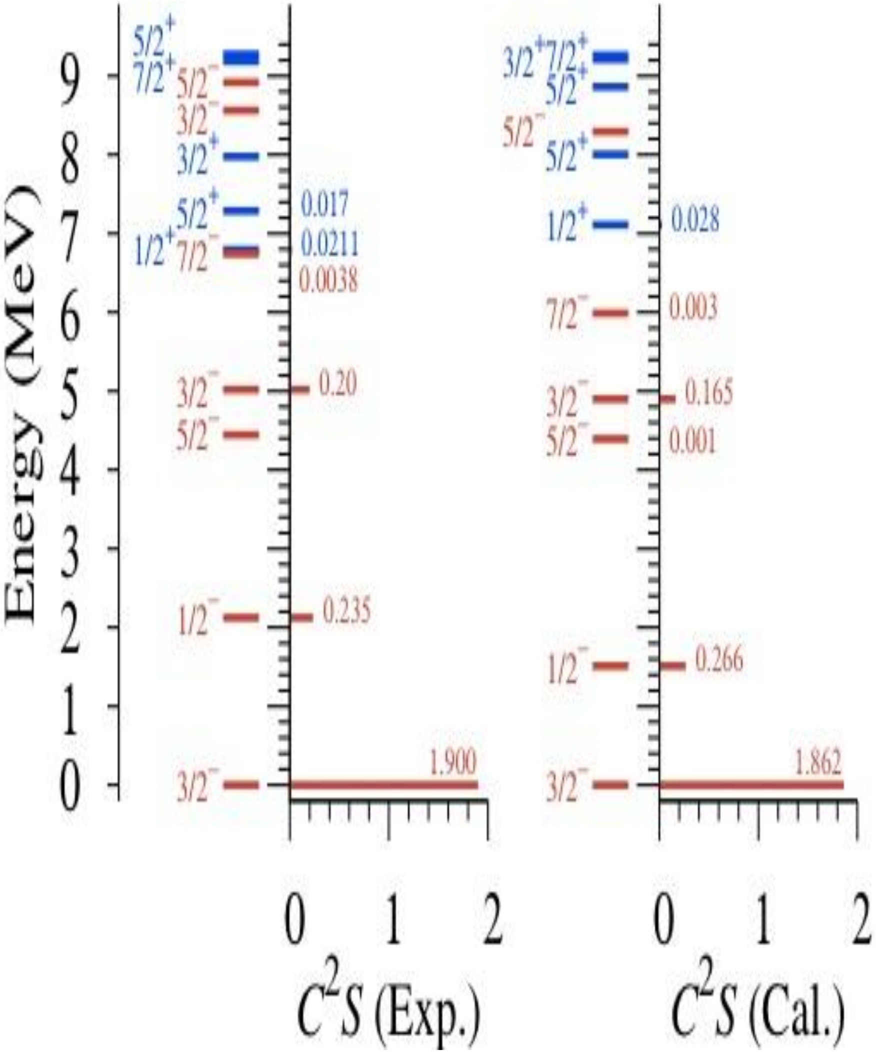
(Relative strengths with respect to the ground-state peak are also shown for reference)

Peak	J_(i)	Ex (MeV) NSC97f	Ex (MeV) DJM	EXP Ex	EXP E_Lam	Theory [nb/sr]	S6B (sum)	Theory [nb/sr]	SLA (sum)	Relative XS w.r.t. GS=100(*) S6B		SLA			Kmaid		RpR
	1-_(1)	0.000	0.00	0.00	-11.508	10.54		21.04		14.3	(Sum)	21.0	(Sum)				
#1	2-_(1)	0.186	0.12	0.17	-11.340	63.05	73.5	89.33	100.37	85.7	100(*)	89.0	100(*)				
#2	1-_(2)	2.398	2.59	3.10	-8.390	18.96	24.1	48.44	56.10	25.8	32.8	48.3	55.9				
	0-_(1)	3.062	2.60			5.18		7.66		7.0		7.6					
	2-_(2)	5.022	5.02			4.90		6.96		6.7		6.9					
	3-_(1)	5.411				(-)		(-)				0.0					
	4-_(1)	6.228				(-)		(-)				0.0					
#3	2-_(3)	6.267	5.64	6.04	-5.488	8.34	15.5	11.84	23.82	11.3	21.1	11.8	23.7				
	3-_(2)	6.356				(-)		(-)				0.0					
	1-_(3)	6.389	5.72			2.29		5.02		3.1		5.0					
	2+_(1)	11.000	10.29			1.34	6.45	1.33	9.49	1.8	8.8	1.3	9.5				
#5	1+_(1)	11.120	10.34	10.22	-1.220	5.11		8.16		6.9		8.1					
#6	3+_(1)	11.081	11.01	10.98	-0.524	57.14	81.1	77.56	130.73	77.7	110.3	77.3	130.3				
	2+_(2)	11.610	10.93			23.95		53.17		32.6		53.0					
	0+_(1)	11.860	11.86			0.18		0.16		0.2		0.2					
	1+_(2)	12.129	12.13			7.03		6.08		9.6		6.1					
#8	2+_(3)	12.784	12.80	12.49	1.047	9.12	20.6	19.96	29.95	12.4	28.0	19.9	29.8				
	1+_(3)	13.176	12.91			4.22		3.74		5.7		3.7					
	0+_(2)	13.772	13.77			0.01		0.01		0.0		0.0					

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



^{11}B



(2015.05.10 Umeya)

Proton pickup S-factor

Our new theoretical challenge

is to take both parity states into account.

major shell mixing mediated by Λ

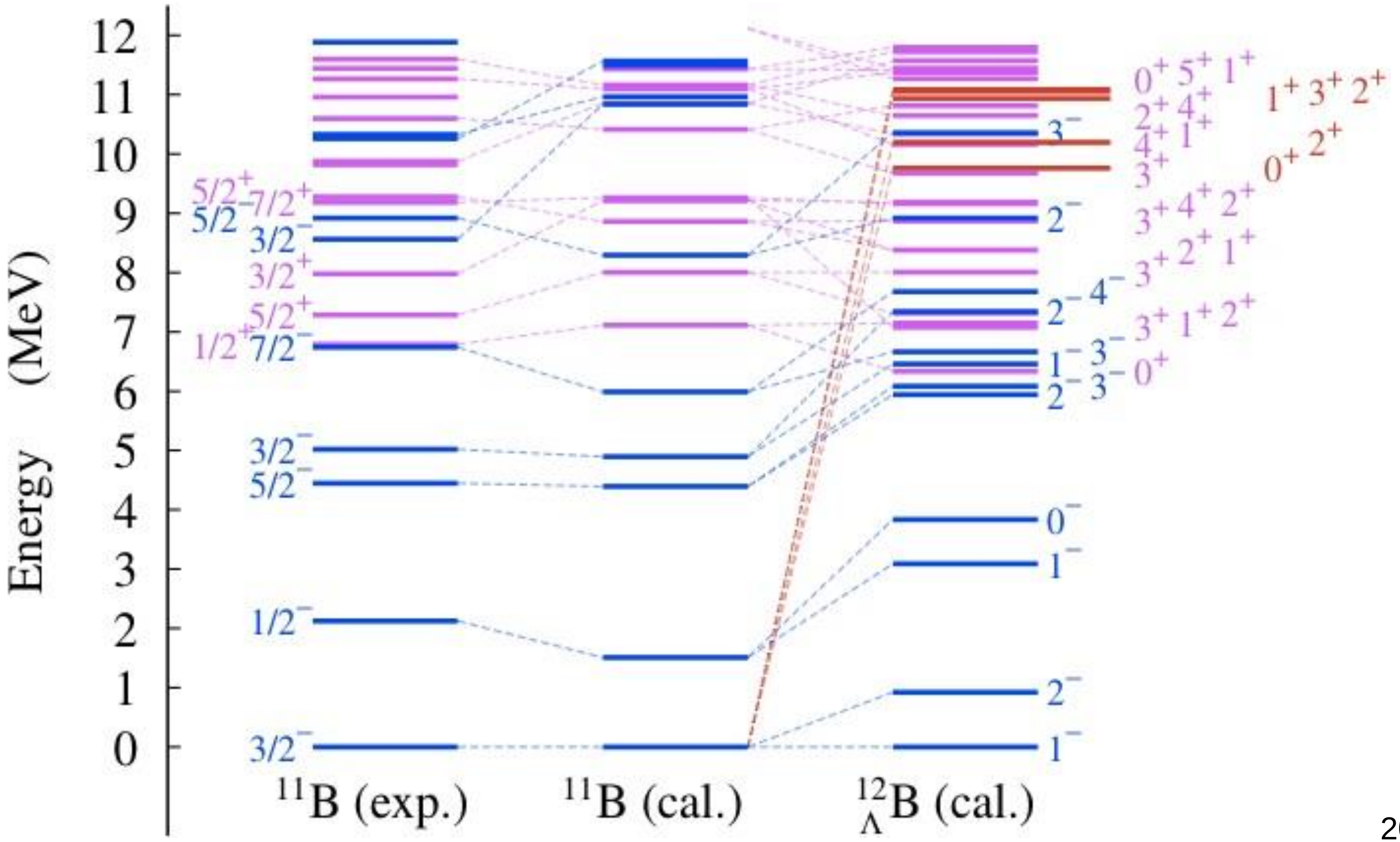
that is a new concept seen only in hypernucleus

(we have called it as parity mixing)

$$ {}^{12}{}_{\Lambda}\mathrm{B}(J_{\mathrm{H}}^{-}) = \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{-})_{0} \times \Lambda_{s} \}^{(0)} + \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{+})_{1} \times \Lambda_{p} \}^{(2)} $$

$$ {}^{12}{}_{\Lambda}\mathrm{B}(J_{\mathrm{H}}^{+}) = \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{-})_{0} \times \Lambda_{p} \}^{(1)} + \{ {}^{11}\mathrm{B}(J_{\mathrm{C}}^{+})_{1} \times \Lambda_{s} \}^{(1)} $$

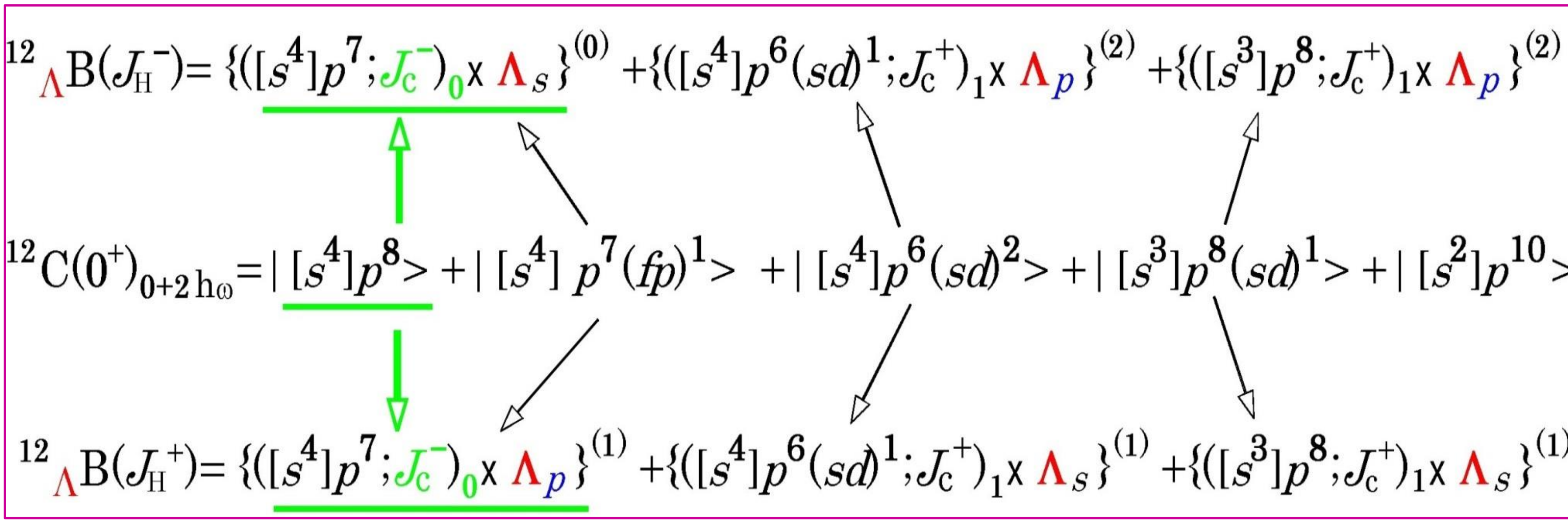
Results of parity mixing calculation (preliminary)



Components connected via (γ,K$^+$)

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

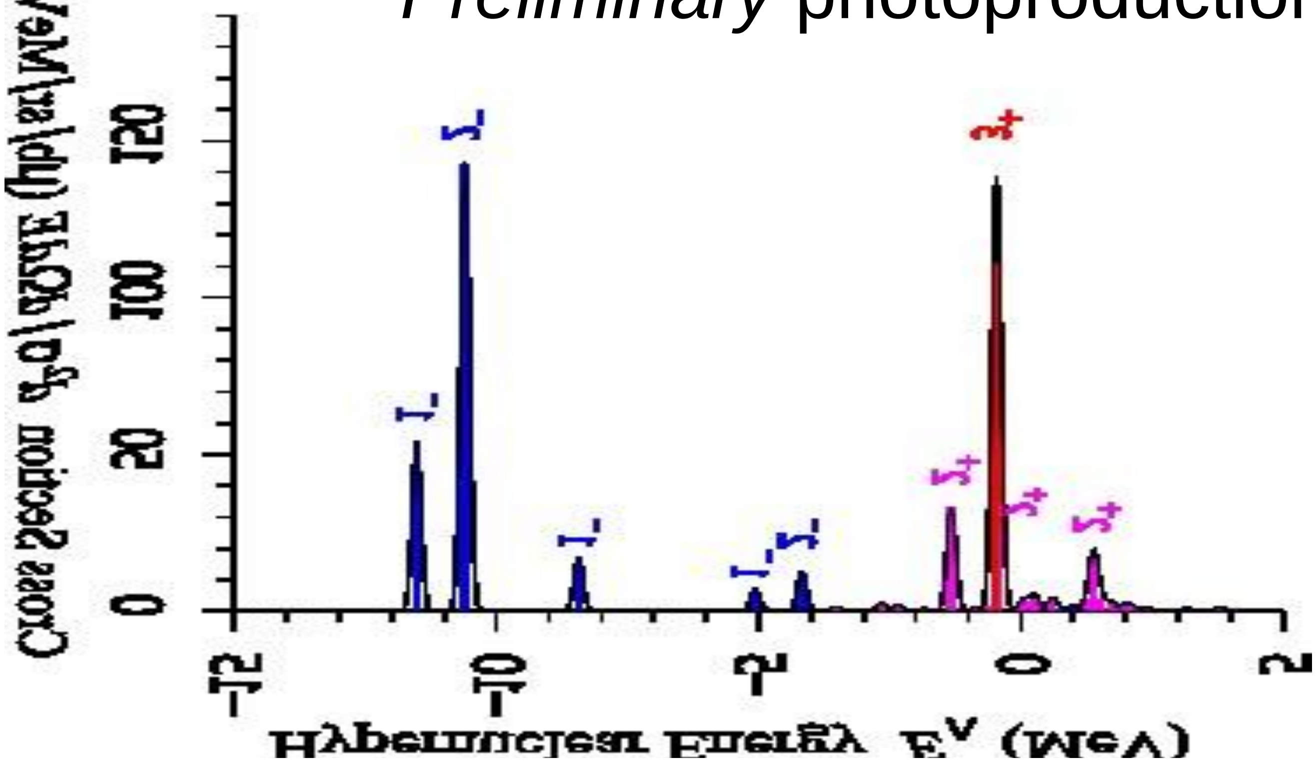
(So far only green arrows are taken into account.)

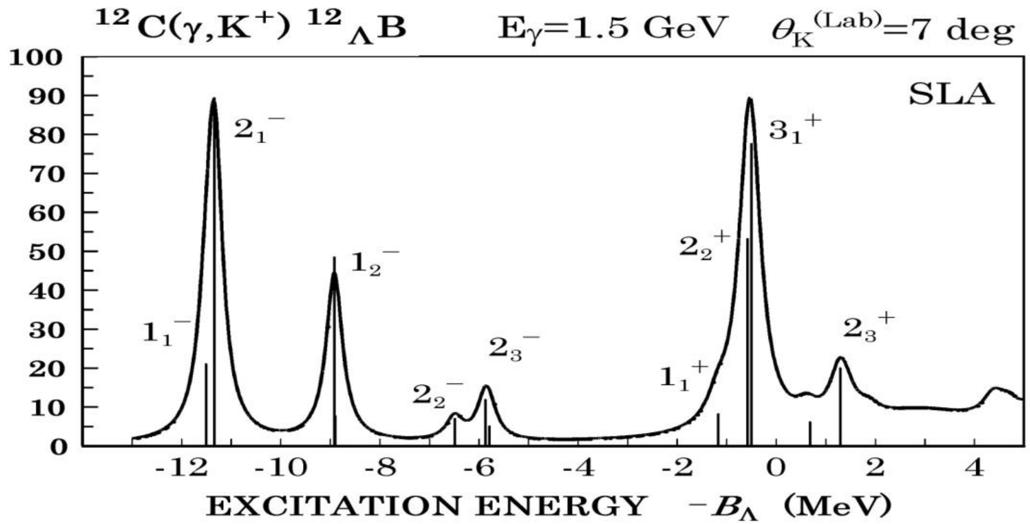


Problems:

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

Preliminary photoproduction X-S





<u>*Down*</u>: Previous calculation

(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* $\gamma p \rightarrow \Lambda K^+$ *process(ability to excite high-spin unnatural-parity states) should be realized **better in heavier systems** involving large* j_p *and large* j_Λ

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

Γ : virtual photon flux (kinematics)

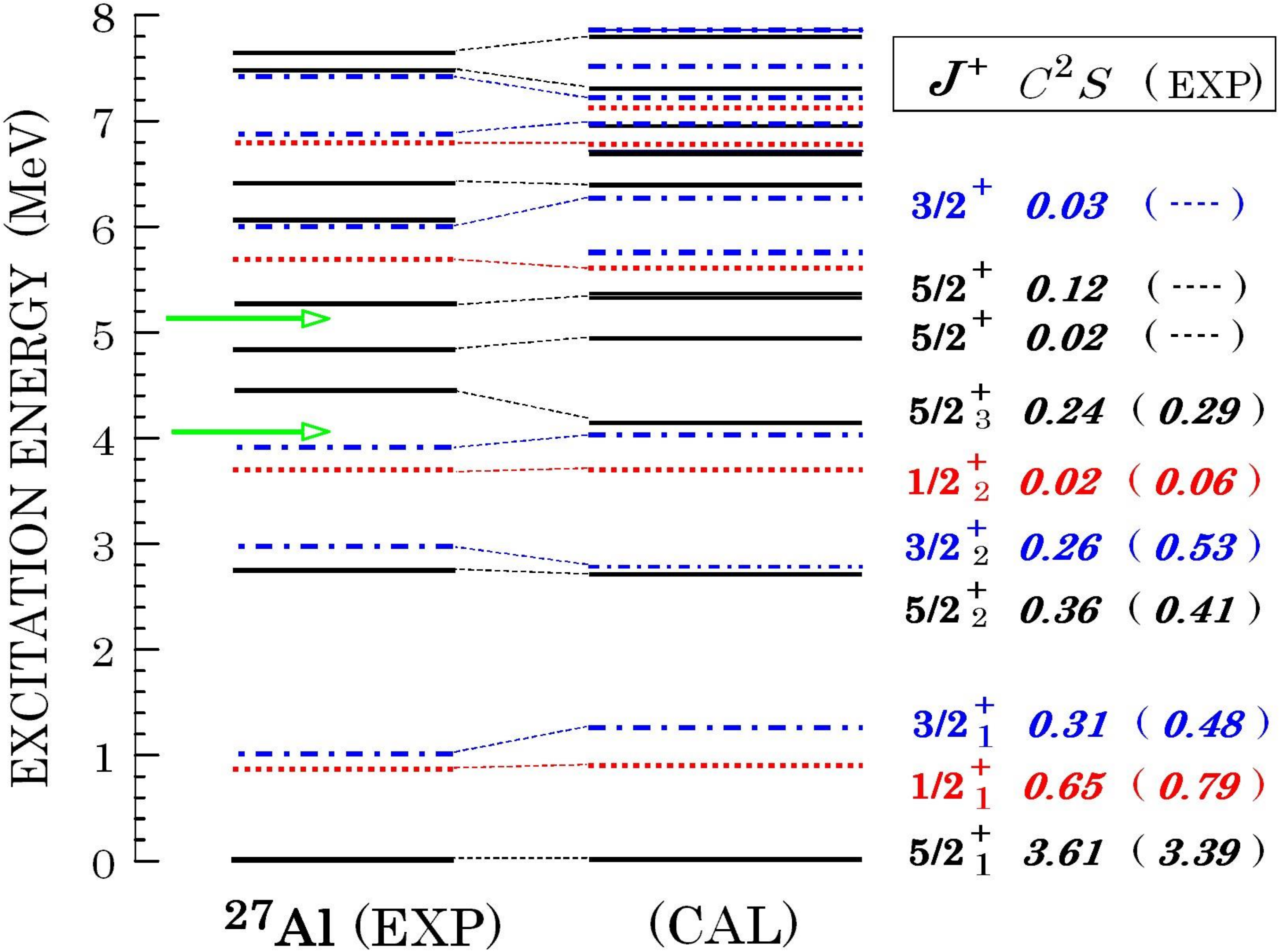
Hereafter we discuss **$d\sigma/d\Omega_K$** for $^{A}Z\ (\gamma, K+)_{\Lambda}{}^{A}Z'$

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

DWIA [nb/sr]

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



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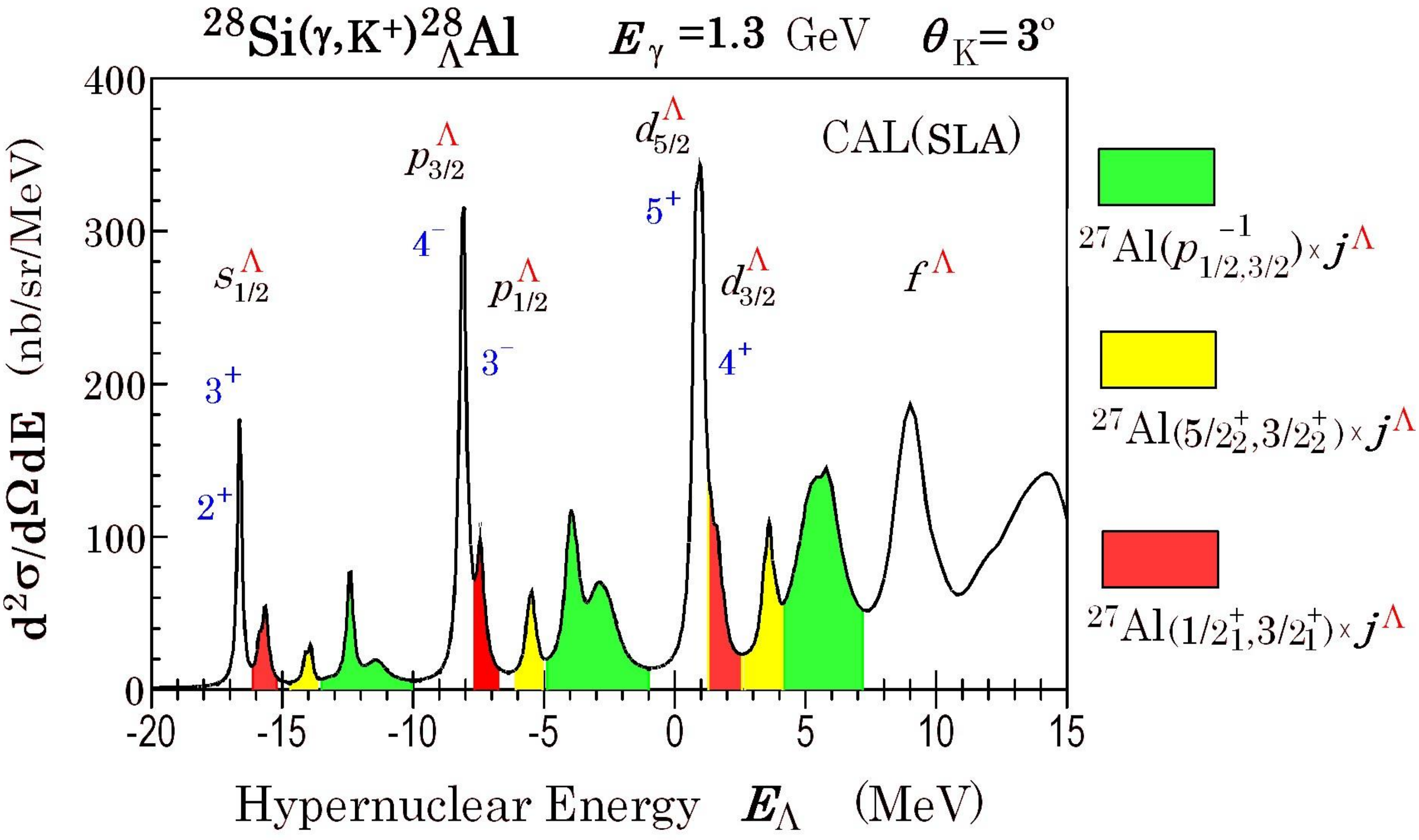
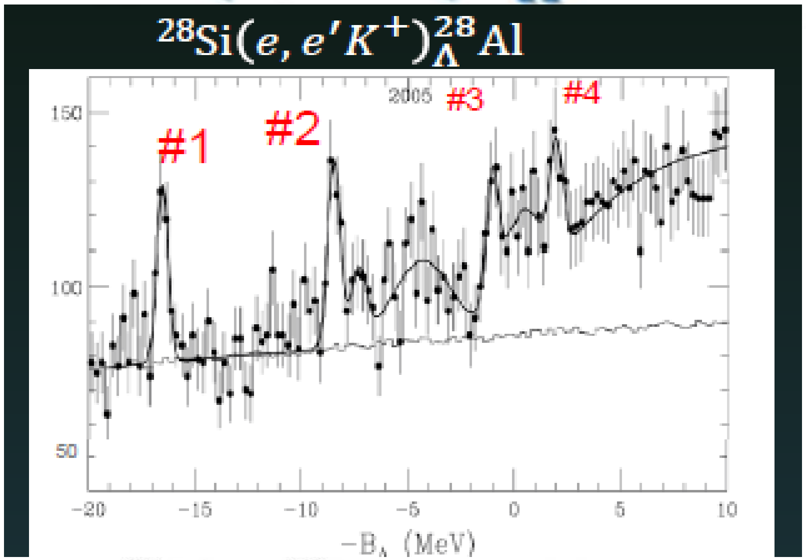
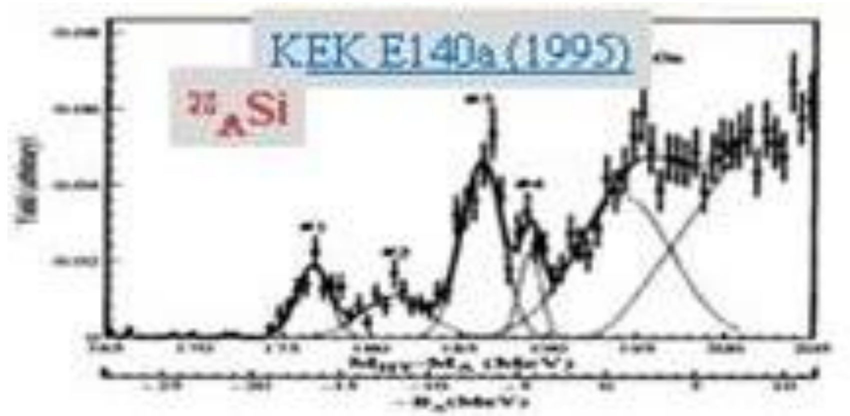
Peaks can be classified by the characters

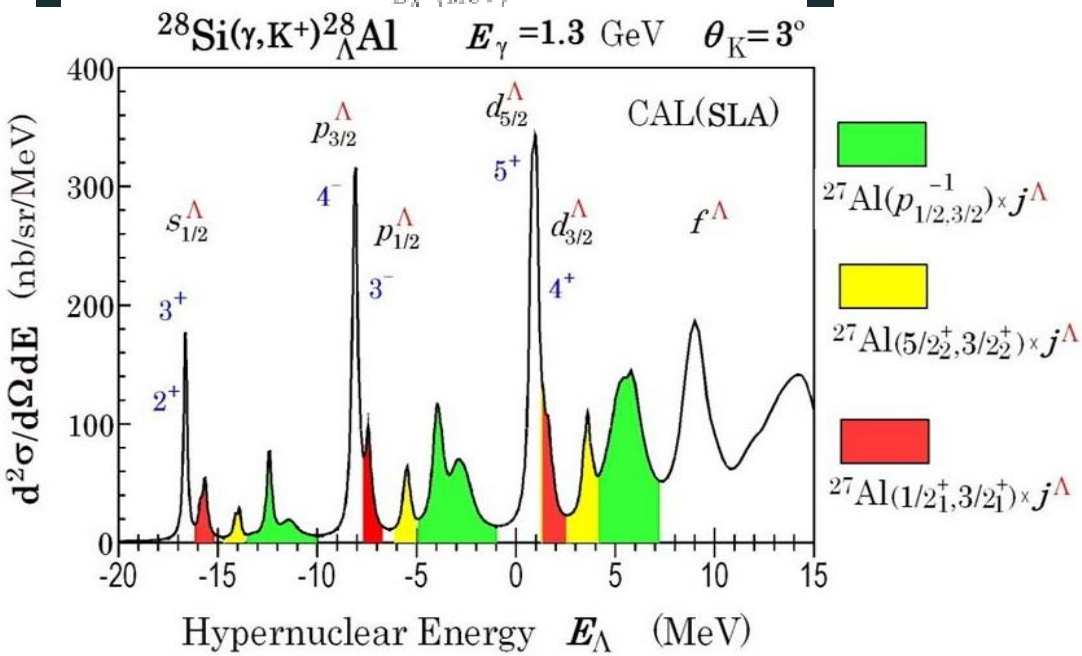


Major peak series : $[^{27}\mathrm{Al}(5/2^+_1)\times j^\Lambda]_J$ with $j^\Lambda = s, p, d, \ldots$

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



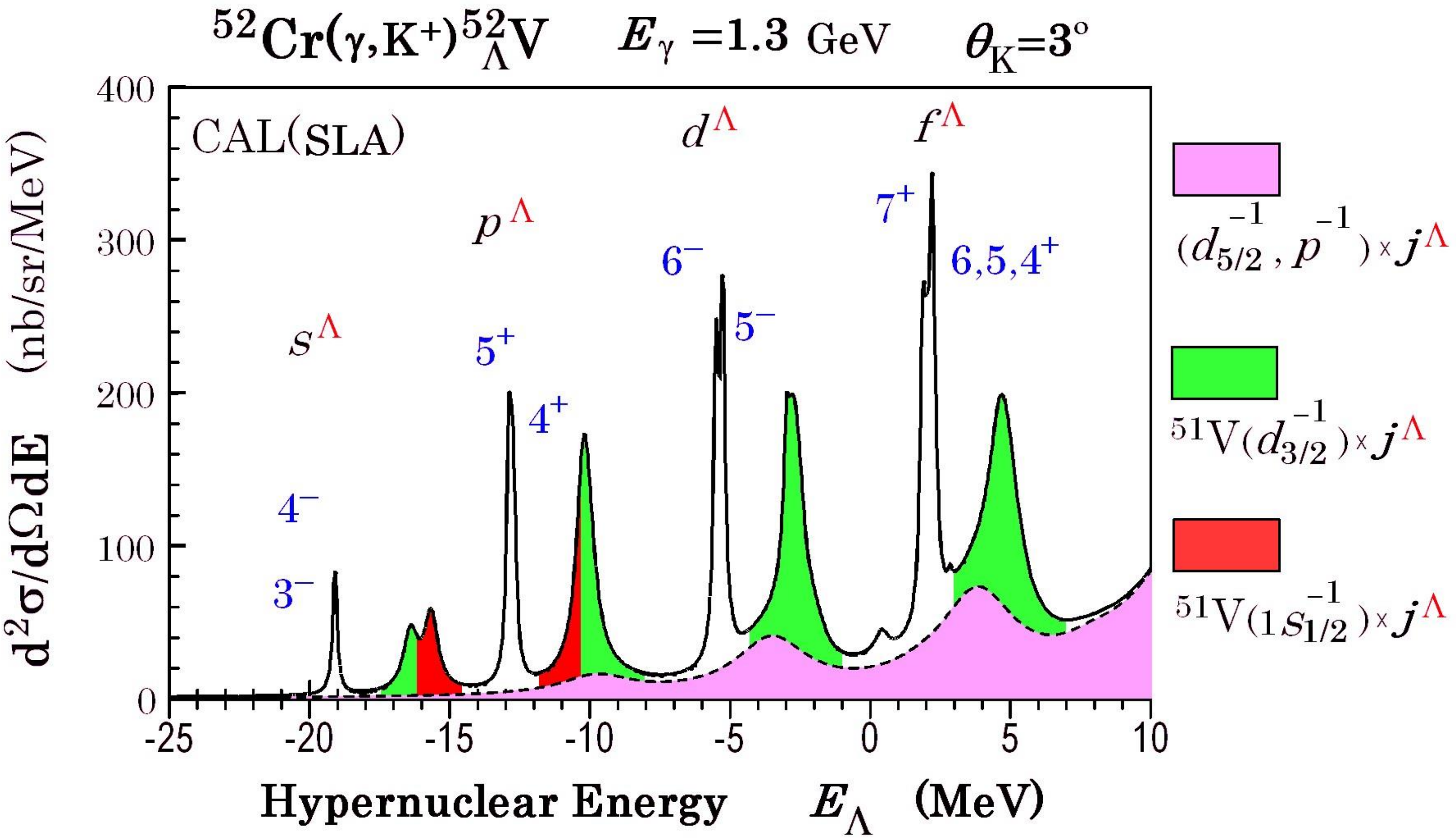




Exp. data:
Nakamura(HYP2015),
Seems promising,
(waiting for finalization of exp. analysis)

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

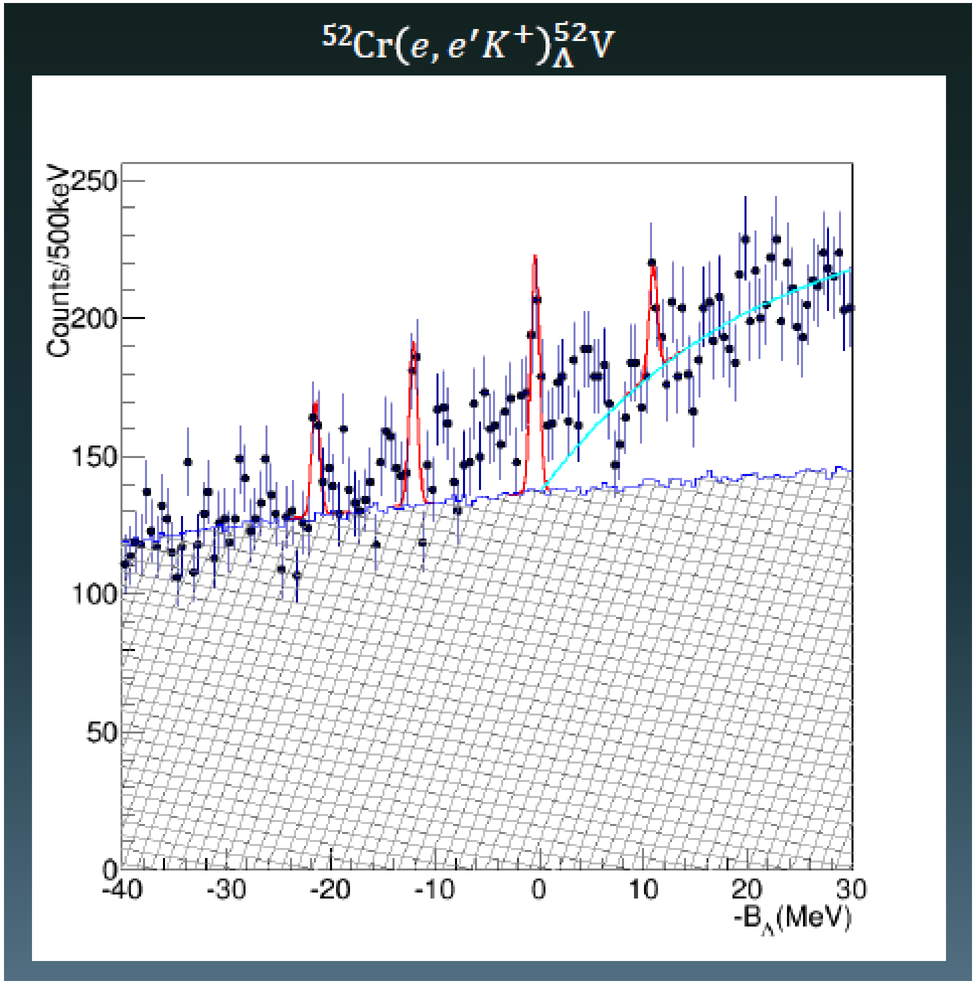
typical unnatural-parity high-spin states



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, priv. commun. (HYP2015)

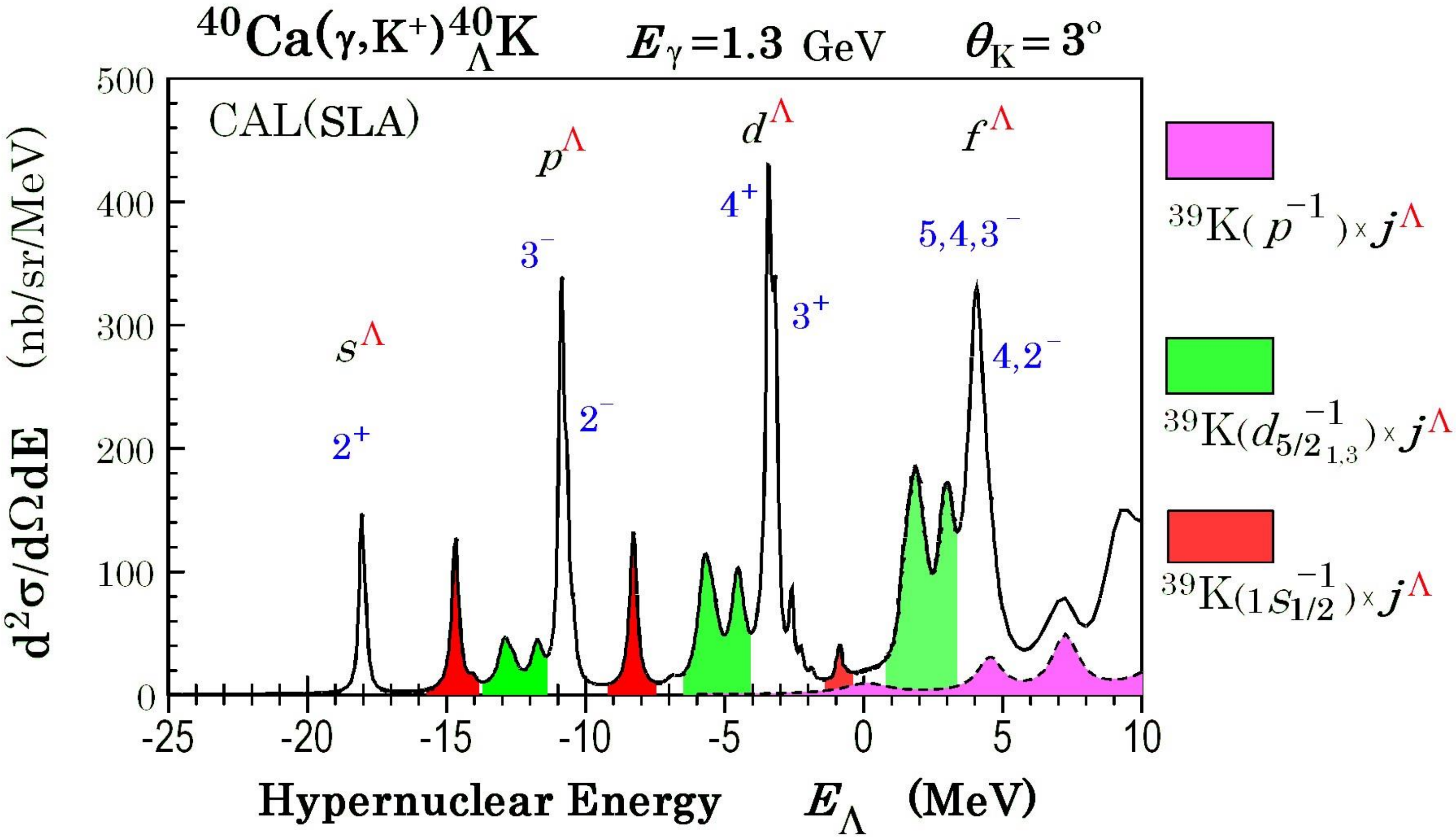


peak	B_{Λ} (MeV)
#1	-21.4
#2	-12.1
#3	-0.4
#4	+10.9

E01-115

^{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 $j^{\Lambda} = s, p, d, f, \ldots$

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)

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

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

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

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

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

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

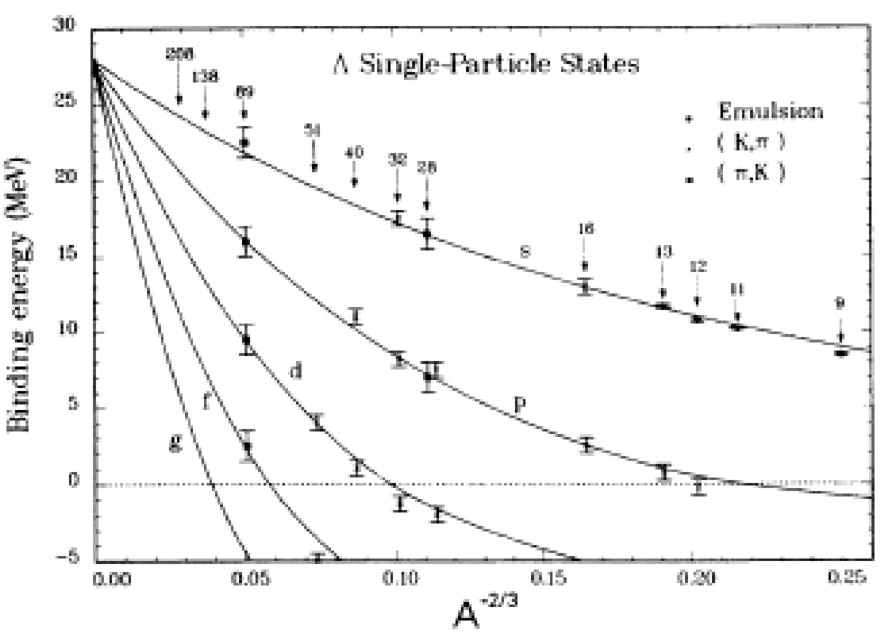


FIG. 1. The data on binding energies (B_Λ) of Λ sing

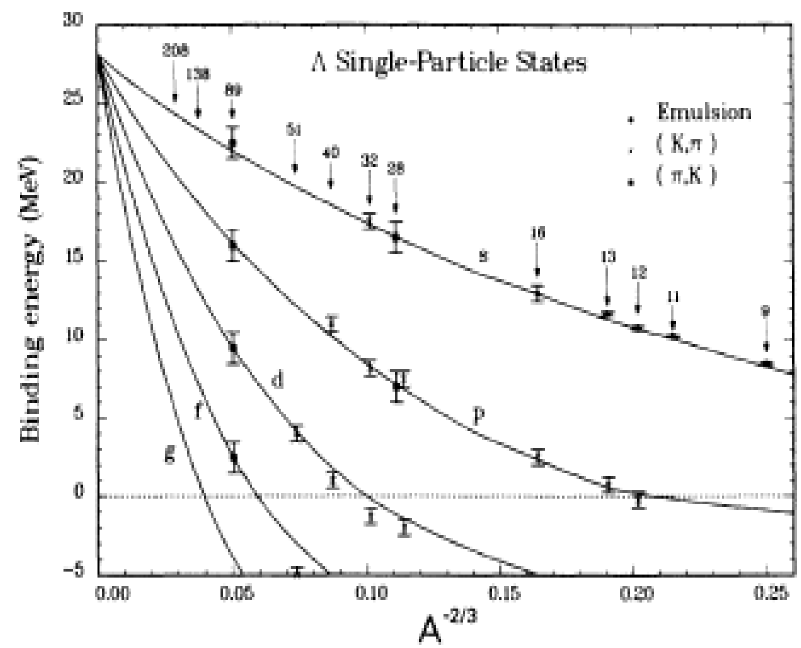


FIG. 5. Same as Fig. 4 but for the potential in Table III with $\rho^{4/3}$ density dependence.

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

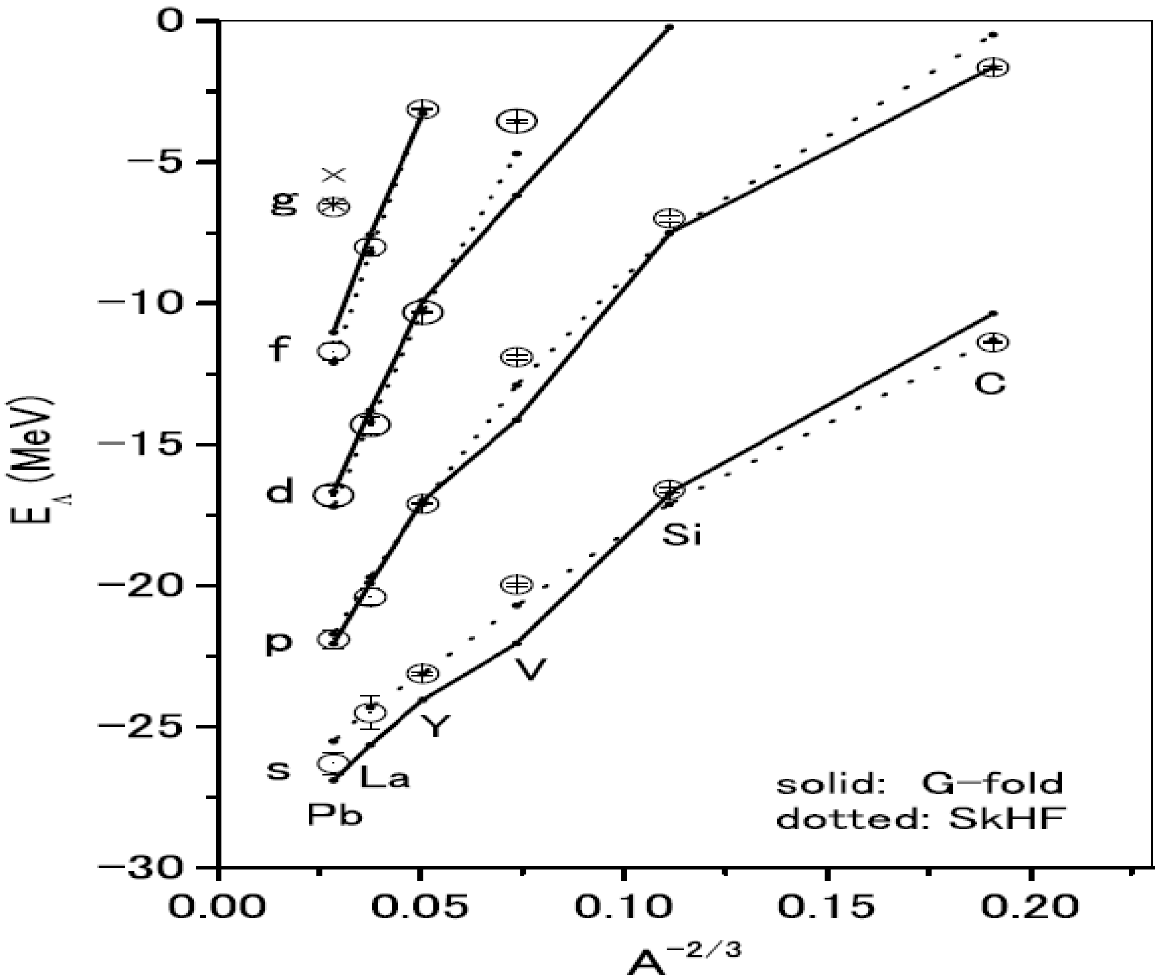
Skyrme HF with ρ^(4/3)
Density dependent

Single-particle energies of Λ

G-matrix（ESC08c） results vs. experiments

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

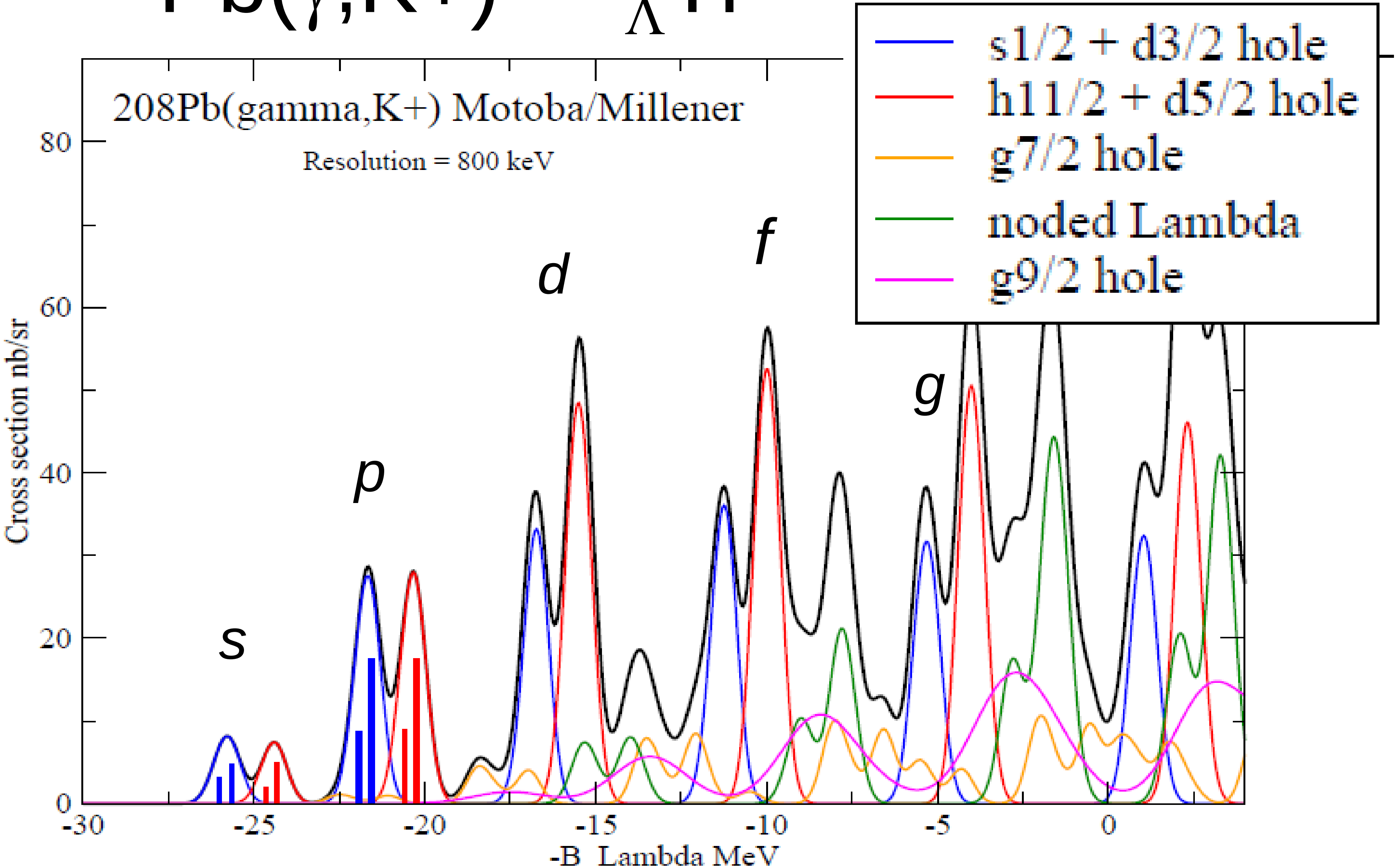
Y. Yamamoto, T. Motoba and Th. A. Rijken



High resolution exp. data over wide A are necessary.

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

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



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*

- Refer to Talks by Isaka and Hagino.

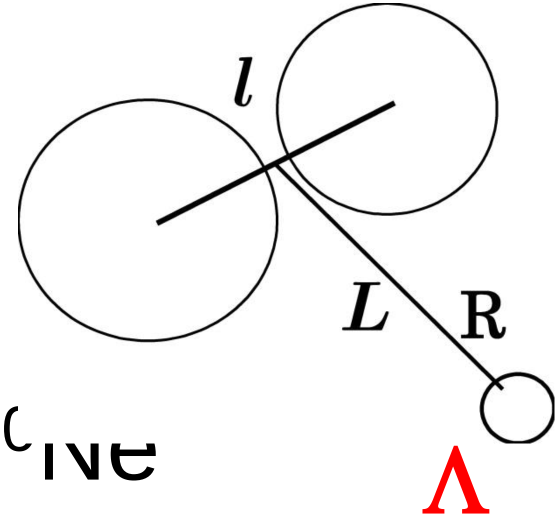
Why the strong coupling is realized between p-state Λ and α+α core ?

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

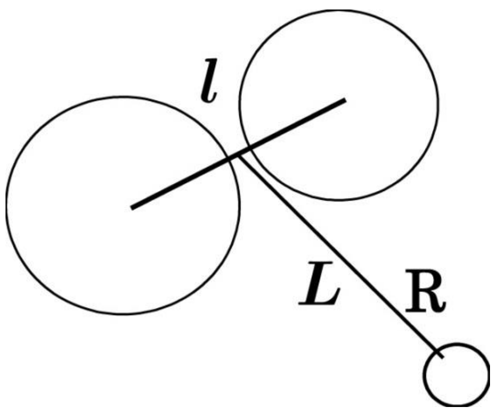
$(\lambda\mu)=(04)$ $\ell=0,2,4^+$ for ^{12}C

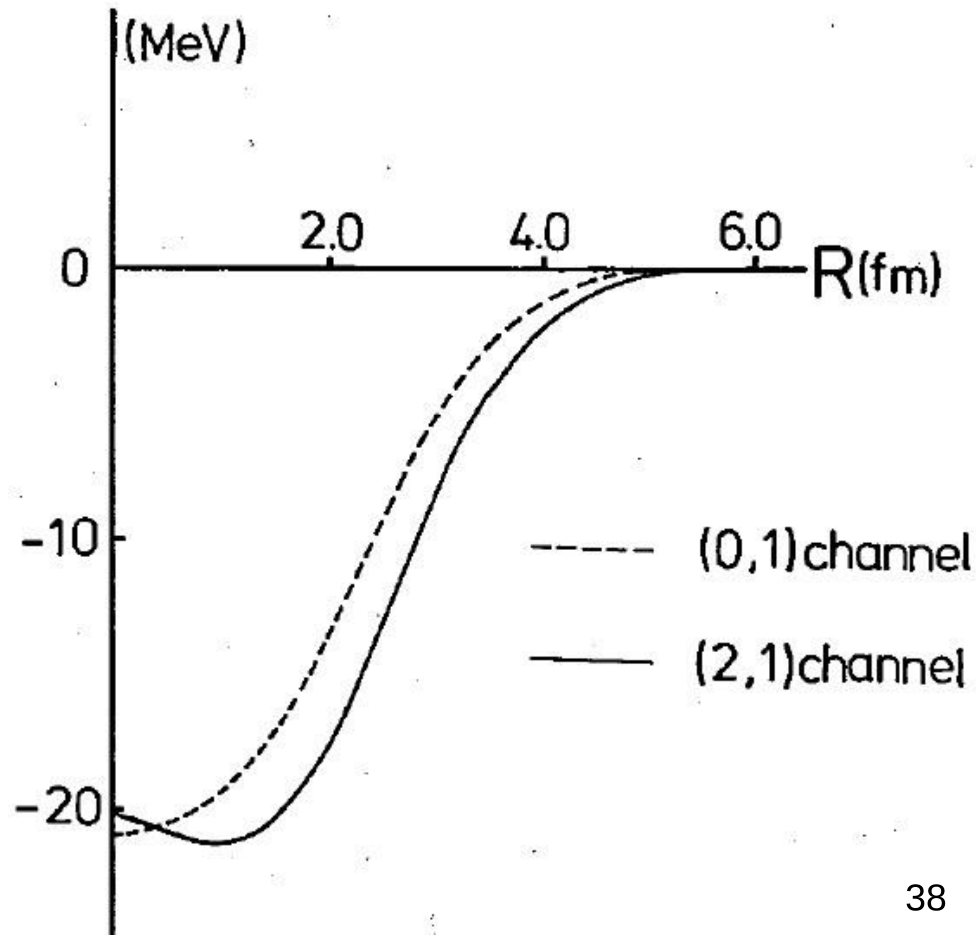
$(\lambda\mu)=(80)$ $\ell=0,2,4,6,8^+$ for ^{20}Ne



l-dependent folding potential

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





Diagonal potential

$V_{lL}(R)$ for Λ *p*-state

l=2 is more attractive than l=0.

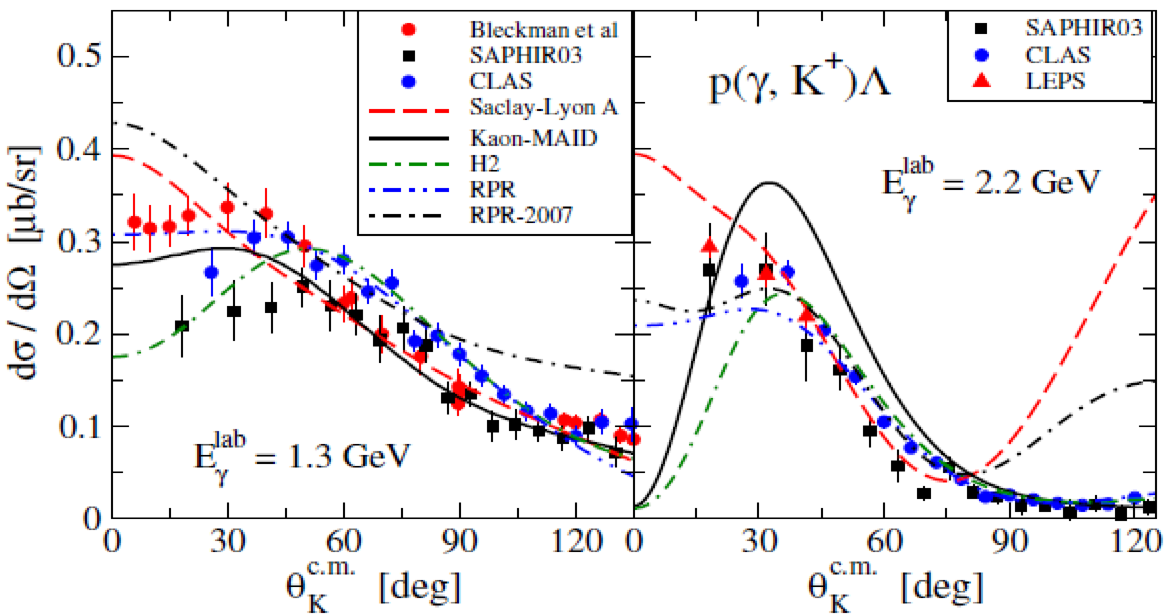
Possible test of $\gamma p \to \Lambda K$ ampl.

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)

Summary and outlook

1) Based on the (γ,K+) reaction characteristics, typical physics contents are discussed by showing theoretical production X-sections.

2) Among others the DWIA predictions for p-shell, ${}^{28}_{\Lambda}$Al and ^{52}Cr are well compared with the recent expt. ^{40}Ca and ^{208}Pb are also demonstrated.

3) In addition to the Λ s.p.e., dynamical coupling of Λ with collective nuclear motion is emphasized.

4) Remarks: For efforts to improve the theoretical elementary amplitudes, refer to Skoupil, Bydzovsky, Mart.