Electroproduction of medium-heavy Λ-hypernuclei

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CONTENTS

1. **Basic motivations** for medium-heavy systems
2. **Go to *sd*-shell: "Simplest" target (^{19}F) and the $(d_{5/2})^6$ model** to demonstrate the present theoretical treatments.
3. **Realistic predictions** for photo-production reaction with a typical target $^{28}\mathrm{Si}(\gamma, K^+)_{\Lambda}{}^{28}\mathrm{Al}$
4. **Extension** of the approach to produce heavier hypernuclei around A=40-52
5. Outlook

1. Basic motivation:

Why medium-heavy hypernuclei ?

(1)

The great success of Hall A and Hall C experiments at Jlab:

-- sub-MeV (Γ= approx. 0.5 MeV)

-- predictions for p-shell confirmed

encourages

extension of high-resolution reaction spectroscopy to heavier hypernuclei:

(K^-,π^-)

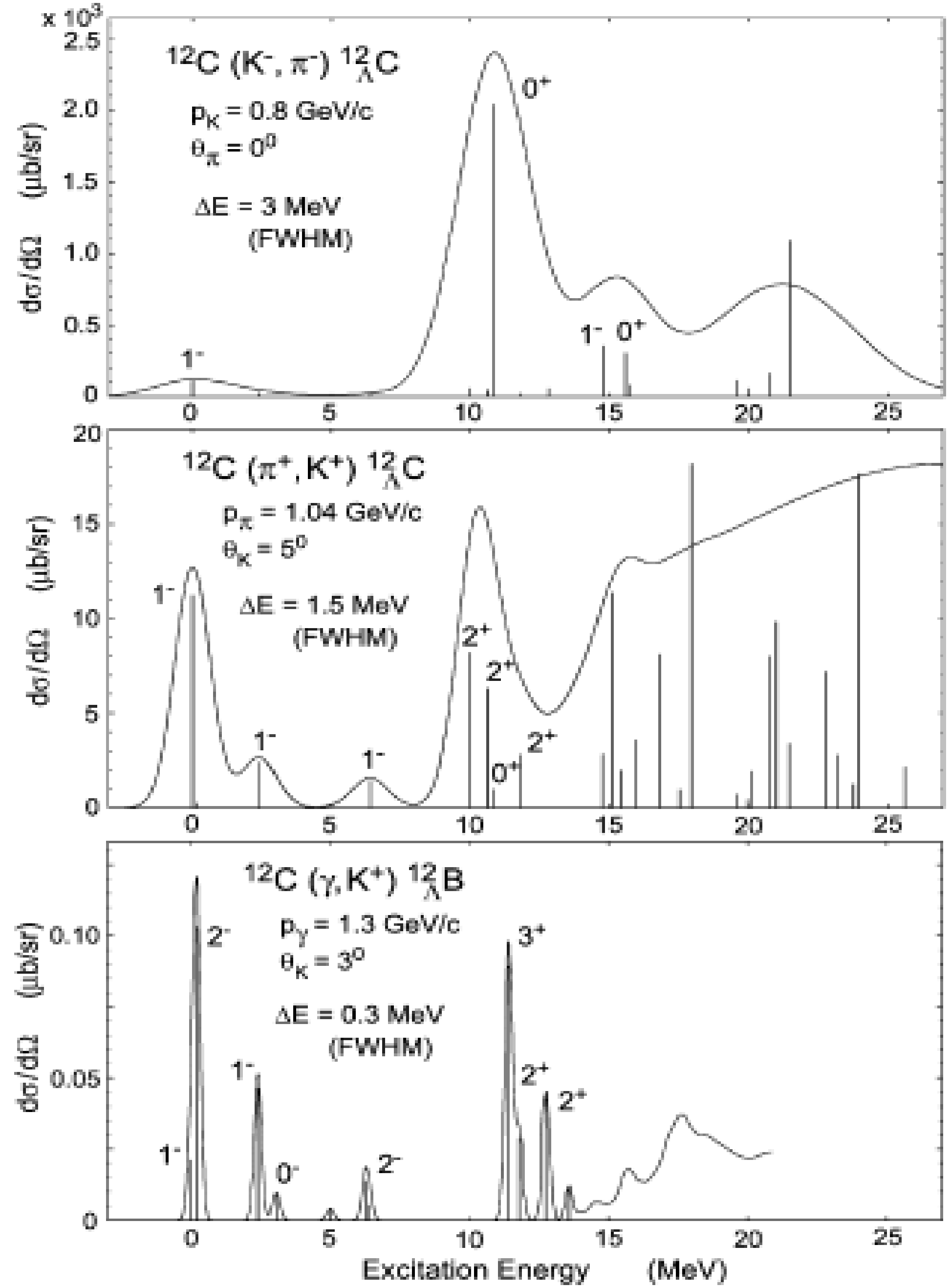
(π^+,K^+)

played a great role of
exciting high-spin series
Γ = 1.5 MeV (best)

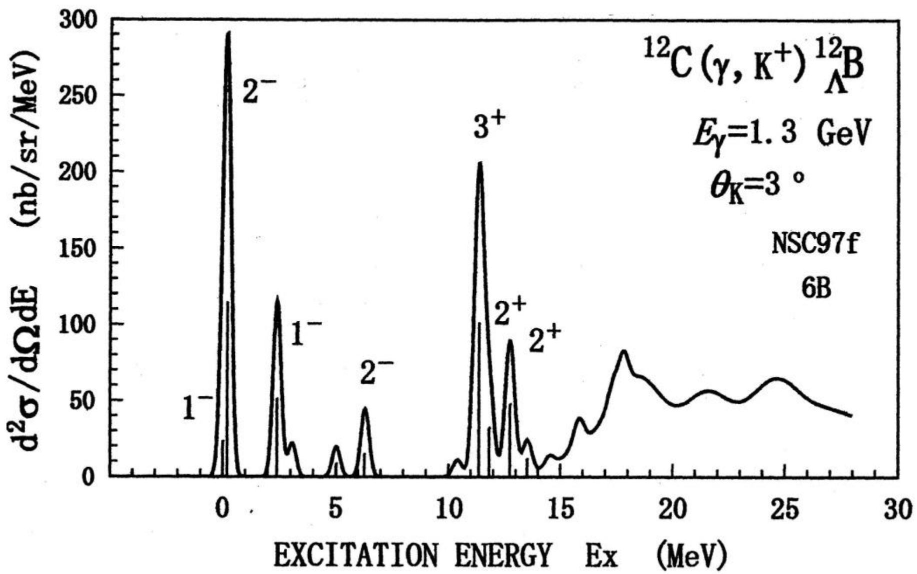
(e,e'K⁺), (γ, K⁺)

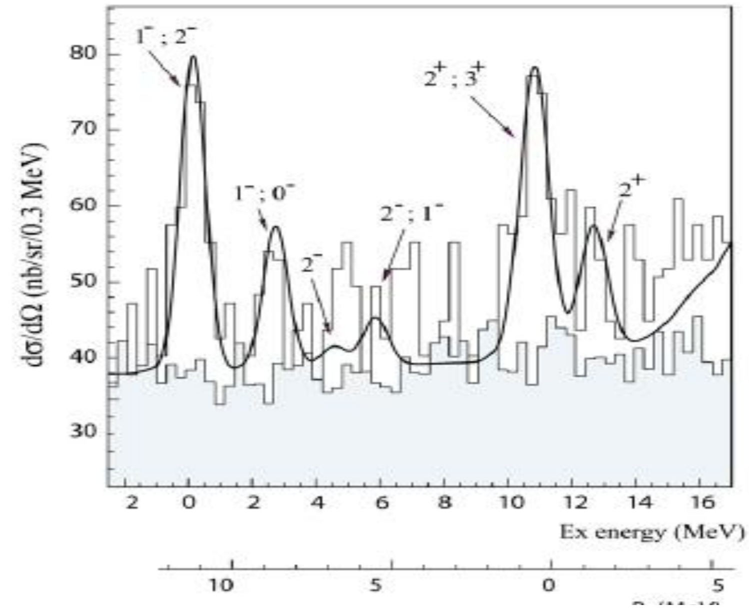
Motoba. Sotona, Itonaga,
Prog.Theor.Phys.S.**117**(1994)
T.M. Mesons & Light Nuclei
(2000) updated w/NSC97f.

JLab Exp't : Γ = 0.5 MeV



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

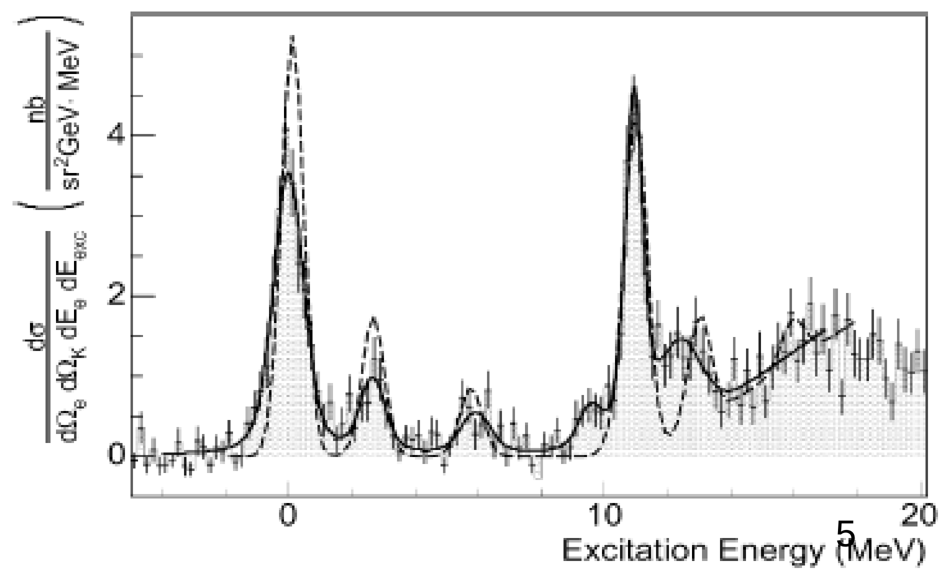




Motoba. Sotona, Itonaga,
Prog.Theor.Phys.Sup.**<u>117</u>** (**1994**)
T.M. *Mesons & Light Nuclei* (2000)
updated w/NSC97f.
-------------------- Sotona's Calc.----→

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**



Why medium-heavy hypernuclei ?

motivation (2)

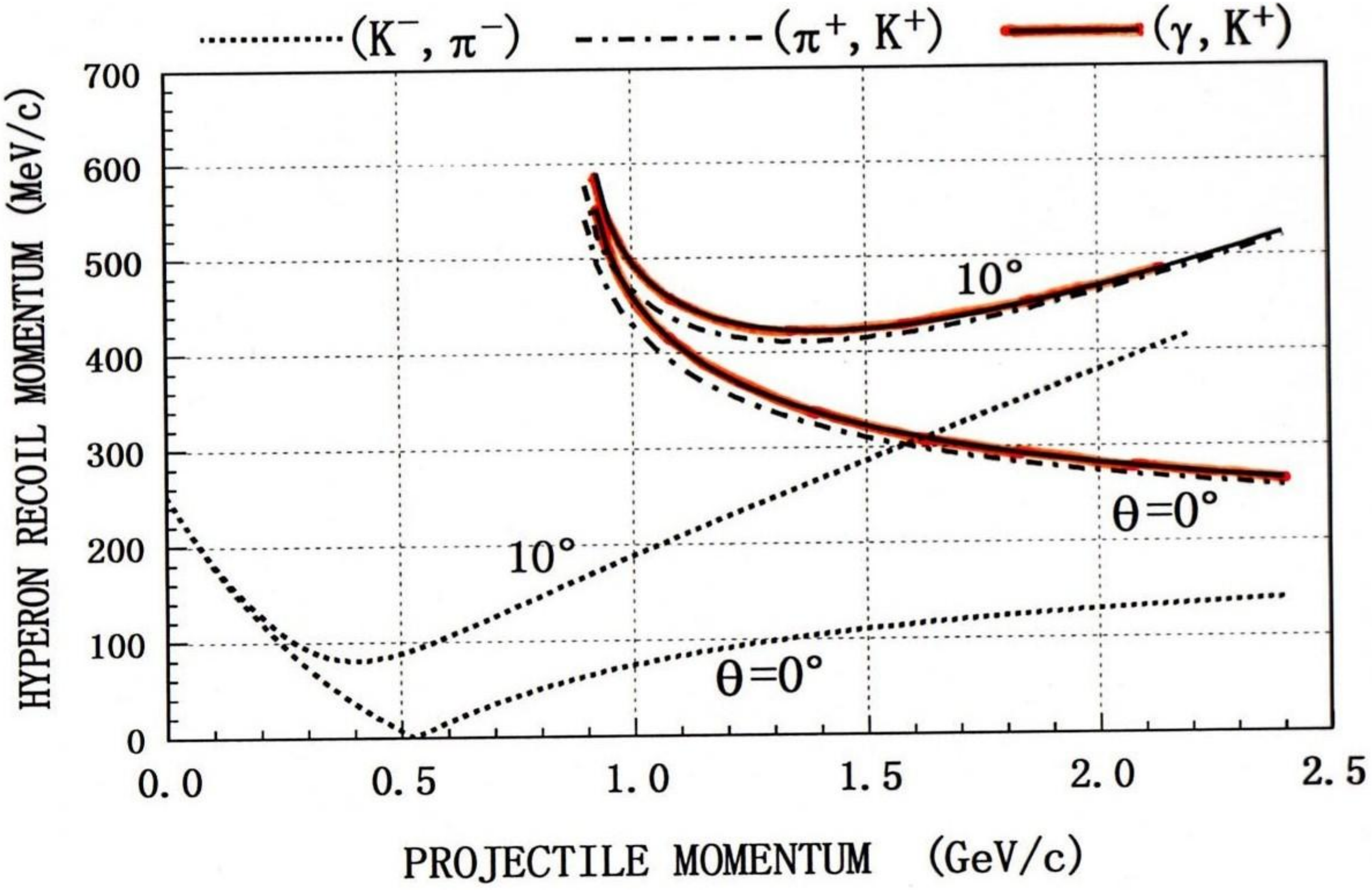
Unique characteristics of the $(e,e'K^+)$, (γ, K^+) process are based on the **basic Properties** of elementary amplitudes for $\gamma\, p \rightarrow \Lambda K^+$:

--- **sizable momentum transfer** to excite high-spin states, like (π^+,K^+)

--- **spin-flip dominance** of the operator, leading to unnatural parity states

Comparison of the recoil momentum

q_{Λ}=350-420 MeV/c at Eγ=1.3 GeV



Elementary amplitudes (2CM): $\gamma p \rightarrow \Lambda K^{+}$

$$\mathcal{M} \equiv \frac{(2\pi)^2}{\sqrt{s}} \sqrt{e_\gamma e_p e_\Lambda e_K} \langle q, -q | t | \kappa, -\kappa \rangle$$

$$= iF_1(\sigma \cdot \epsilon) + F_2(\sigma \cdot \hat{q})[\sigma \cdot (\hat{\kappa} \times \epsilon)] + iF_3(\sigma \cdot \hat{\kappa})(\hat{q} \cdot \epsilon) + iF_4(\sigma \cdot \hat{q})(\hat{q} \cdot \epsilon) .$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{2CM} = \frac{q}{\kappa} \Big\{ |F_1|^2 + |F_2|^2 - 2\cos\theta_{CM} \operatorname{Re}(F_1^* F_2)$$

$$+ \frac{1}{2}\sin^2\theta_{CM}[|F_3|^2 + |F_4|^2 + \operatorname{Re}(F_1^* F_4 + F_2^* F_3 + F_3^* F_4 \cos\theta_{CM})] \Big\} ,$$

$$\mathcal{P}_Y \left.\frac{d\sigma}{d\Omega}\right|_{2CM} = \frac{q}{\kappa} \sin\theta_{CM} \operatorname{Im}\Big\{ -2F_1^* F_2 - F_1^* F_3 + F_2^* F_4 + \sin^2\theta_{CM} F_3^* F_4$$

$$+ \cos\theta_{CM}[F_2^* F_3 - F_1^* F_4] \Big\} ,$$

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

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

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

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:

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

$$g_0=a_1,$$

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

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 with large j_p and large j_Λ

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

Γ : virtual photon flux (kinematics)

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

2. Go to *sd*-shell:

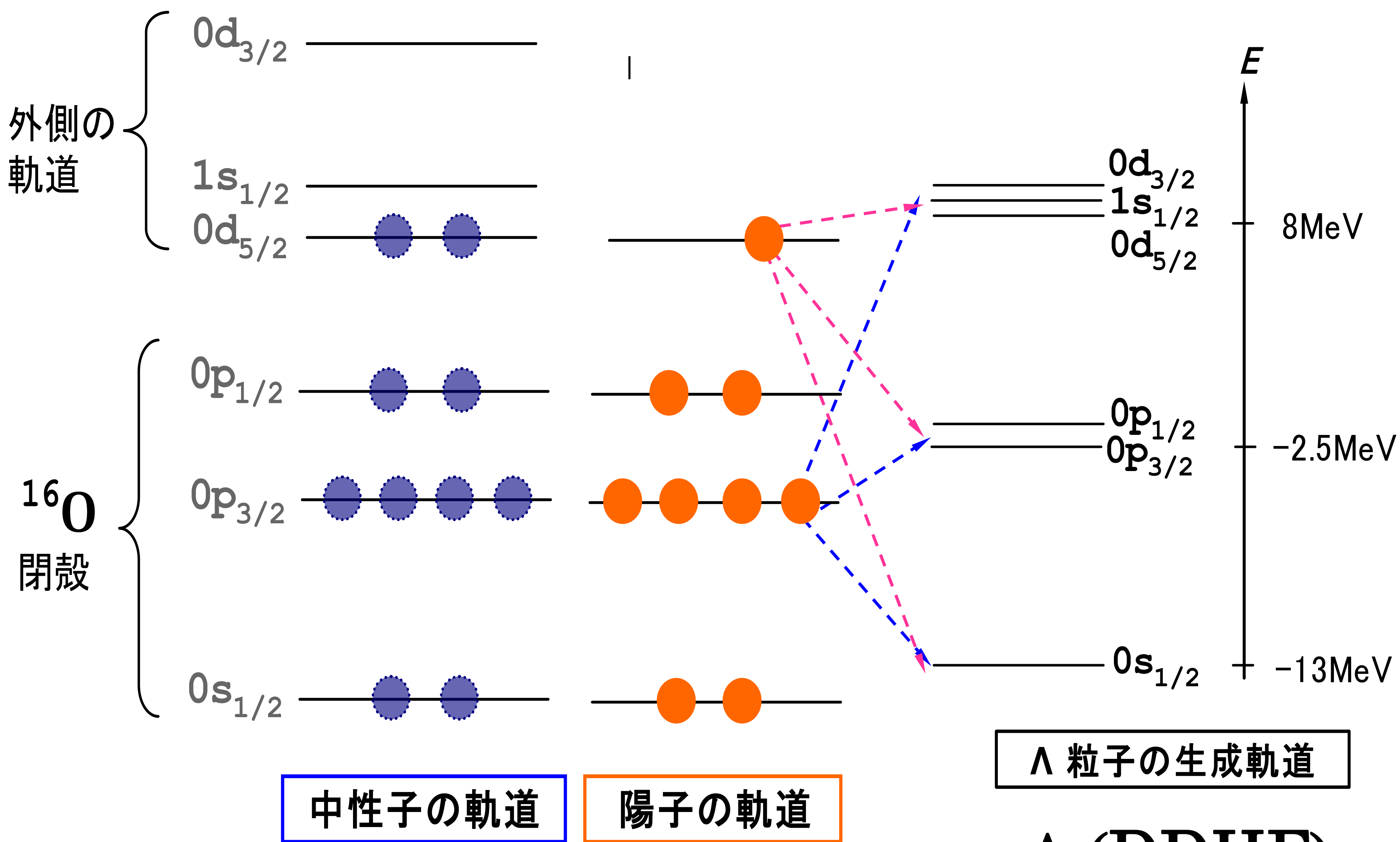
2-1. Simplest sd-shell target

Choose ^{19}F(1/2$^+$) target

for demonstration of the hypernuclear photoproduction

(asking the feasibility as a practical target)

Choose $^{19}F(1/2^+)$ target for demonstration



neutron

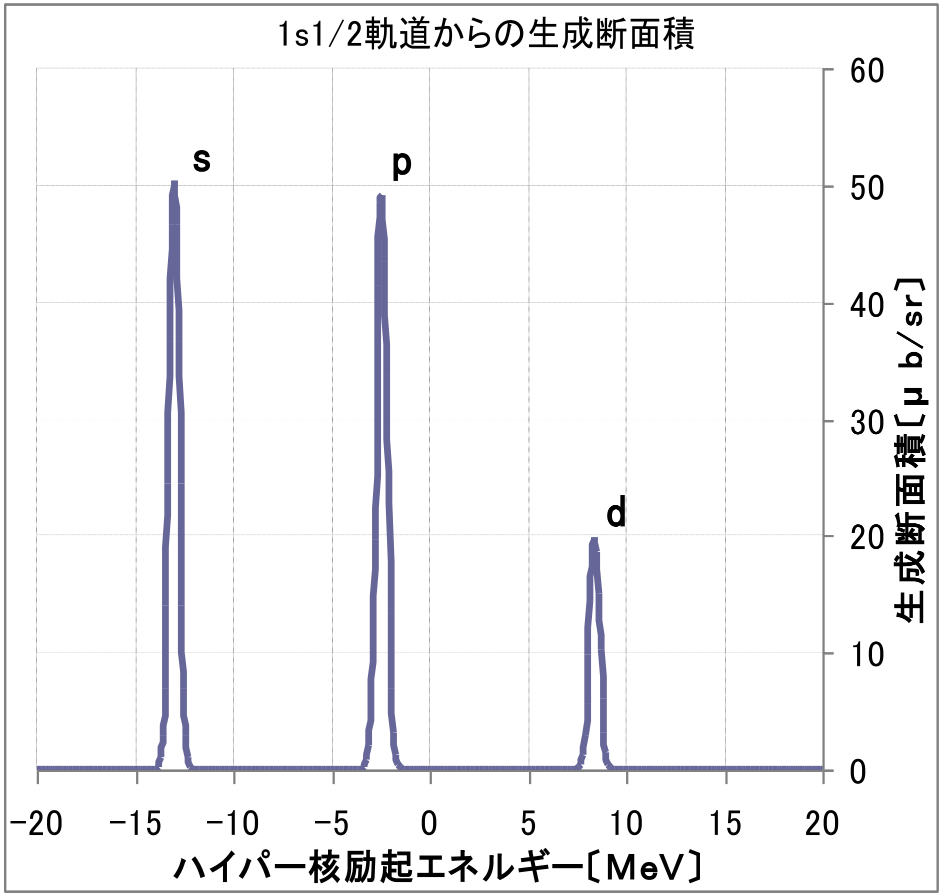
proton

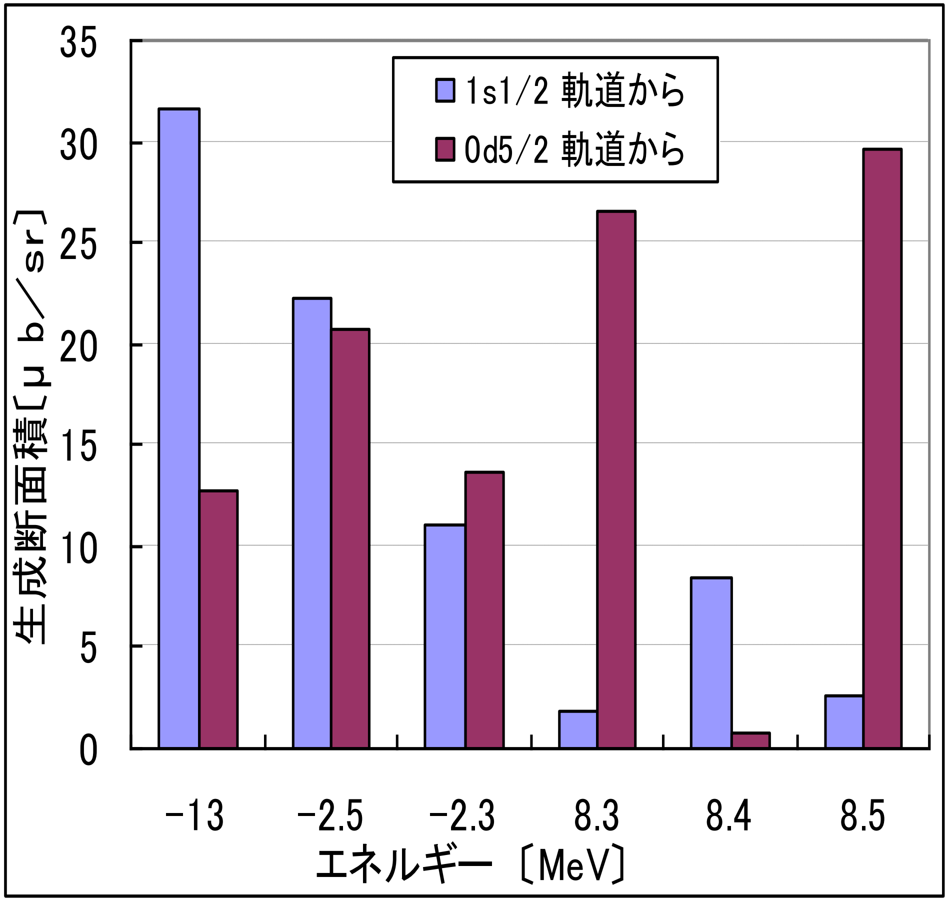
Λ (DDHF)

Partial contributions

Cf. a trial calculation:
If the last odd proton were in $0d_{5/2}$, then

Conversion of $1s_{1/2}$-proton(nb/sr)

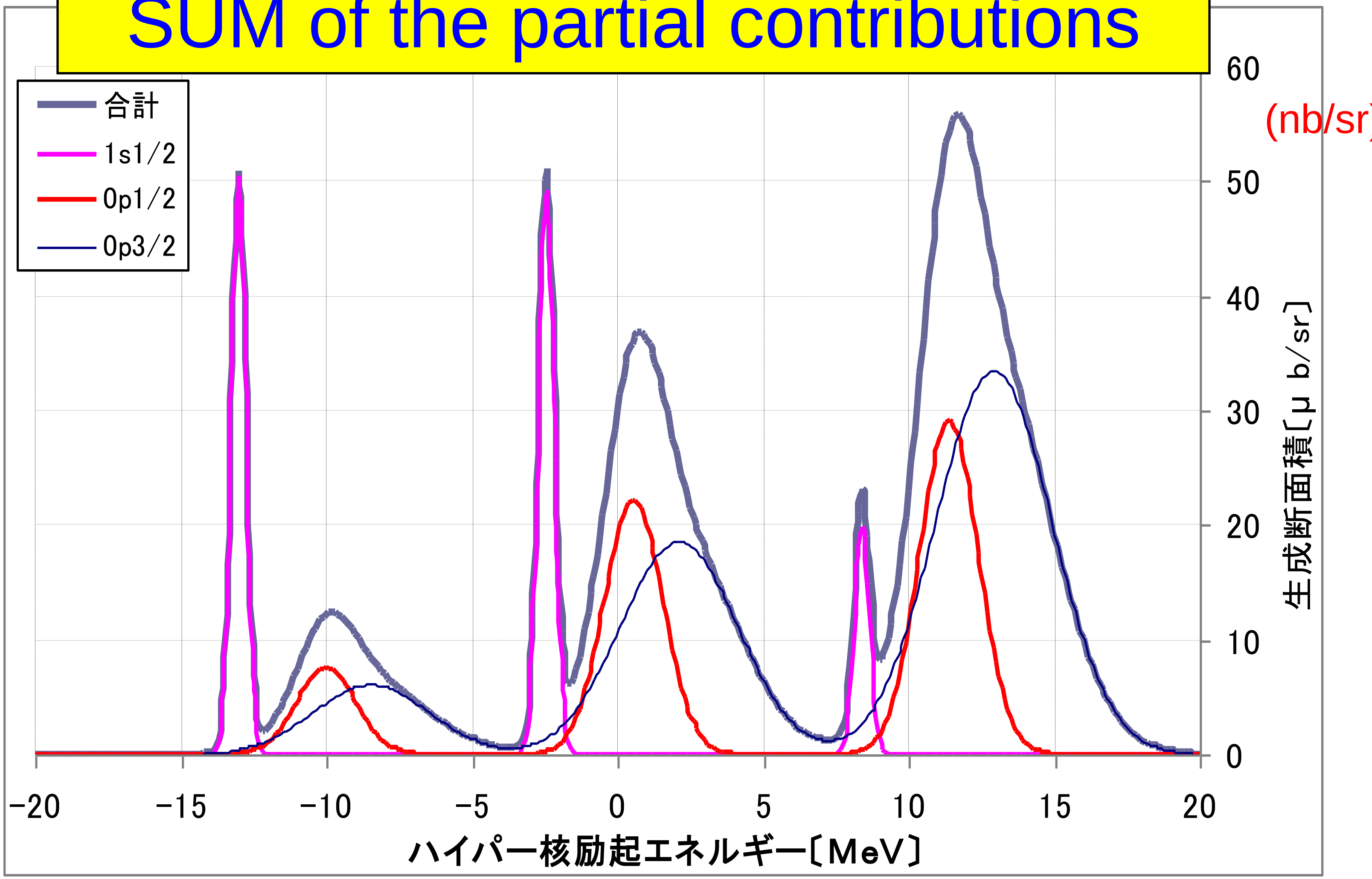




XS in nb/sr (correct units in the above figs.)

$^{19}F(\gamma,K^+)\ _{\Lambda}^{19}O$

SUM of the partial contributions



As a “closed core (^{18}O)”+ Λ， cf. SO-splitting(0p)=152+-54 keV(C13)

2-1. Single-*j* model for the ^{28}Si target

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

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)

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

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

XS(J)

DWIA

(65%)

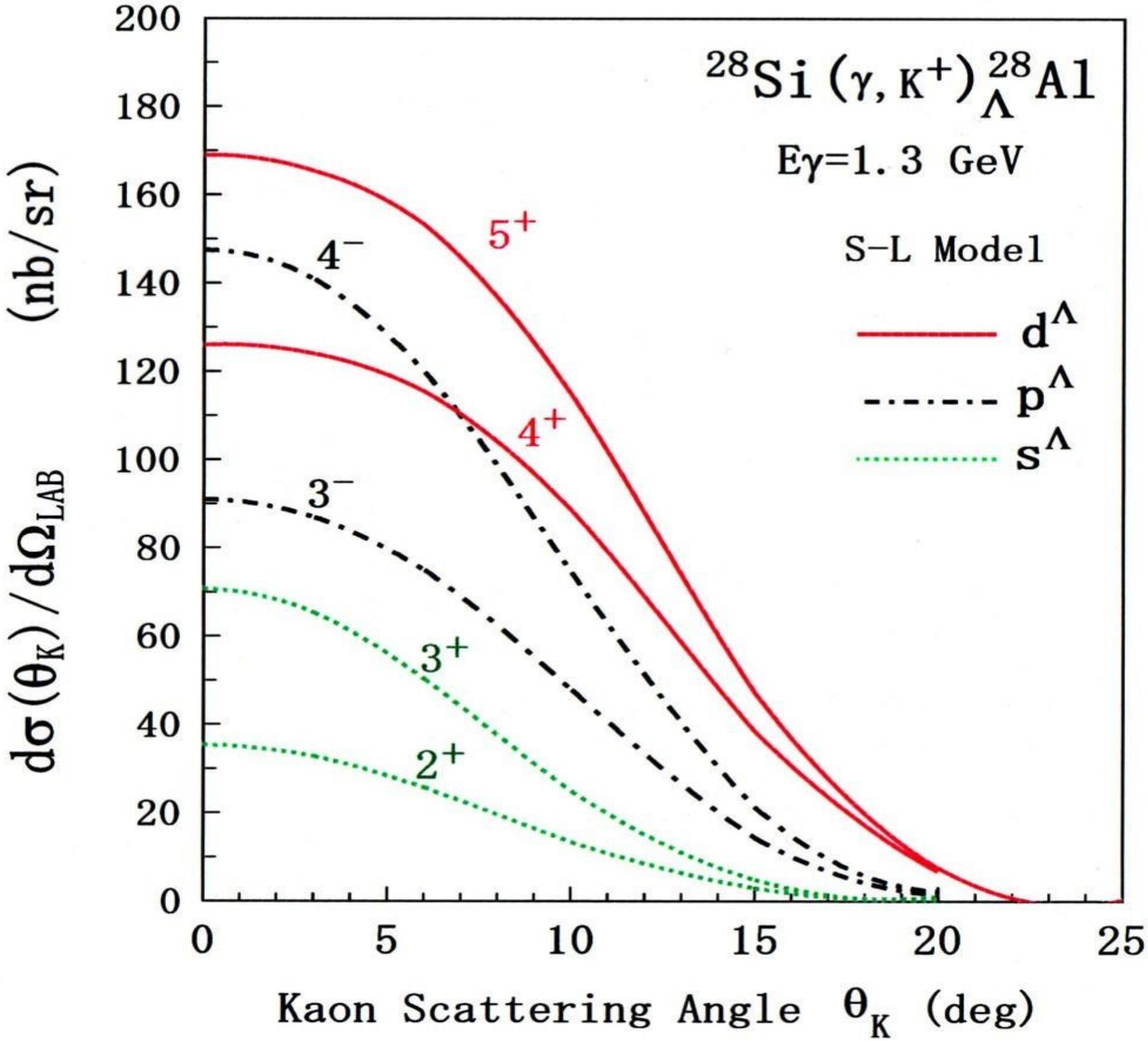
	(a) DWIA	$0s^{\Lambda}_{1/2}$	$0p^{\Lambda}_{3/2}$	$0p^{\Lambda}_{1/2}$	$0d^{\Lambda}_{5/2}$	$0d^{\Lambda}_{3/2}$	$1s^{\Lambda}_{1/2}$
	(E_{Λ})	(−16.92)	(−8.40)	(−8.40)	(0.69)	(0.69)	(0.32)
(p-hole)	$J=0$	–	–	–	0.1	–	–
	$J=1$	–	5.3	–	27.6	7.2	–
($0d^{-1}_{5/2}$)	$J=2$	32.9	2.9	15.7	0.2	33.6	1.6
	$J=3$	65.5	4.6	87.0	20.6	31.1	3.1
	$J=4$	–	141.0	–	0.3	124.1	–
	$J=5$	–	–	–	165.4	–	–

vs.

PWIA

	(b) PWIA	$0s^{\Lambda}_{1/2}$	$0p^{\Lambda}_{3/2}$	$0p^{\Lambda}_{1/2}$	$0d^{\Lambda}_{5/2}$	$0d^{\Lambda}_{3/2}$	$1s^{\Lambda}_{1/2}$
	(E_{Λ})	(−16.92)	(−8.40)	(−8.40)	(0.69)	(0.69)	(0.32)
(p-hole)	$J=0$	–	–	–	0.2	–	–
	$J=1$	–	10.9	–	59.6	15.3	–
($0d^{-1}_{5/2}$)	$J=2$	68.3	4.03	33.4	0.4	71.9	1.4
	$J=3$	135.6	8.3	155.3	46.5	58.9	2.7
	$J=4$	–	250.5	–	0.4	186.9	–
	$J=5$	–	–	–	248.1	–	–

dσ/dΩ(θ_K): angular dependence



$(sp)^{16}(d_{5/2})^{12}$

Model

3. Realistic prediction for $^{28}Si\ (\gamma,K^+)\ {}_{\Lambda}^{28}Al$

By fully taking account of

-- full p(sd)^6.n(sd)^6 configurations,

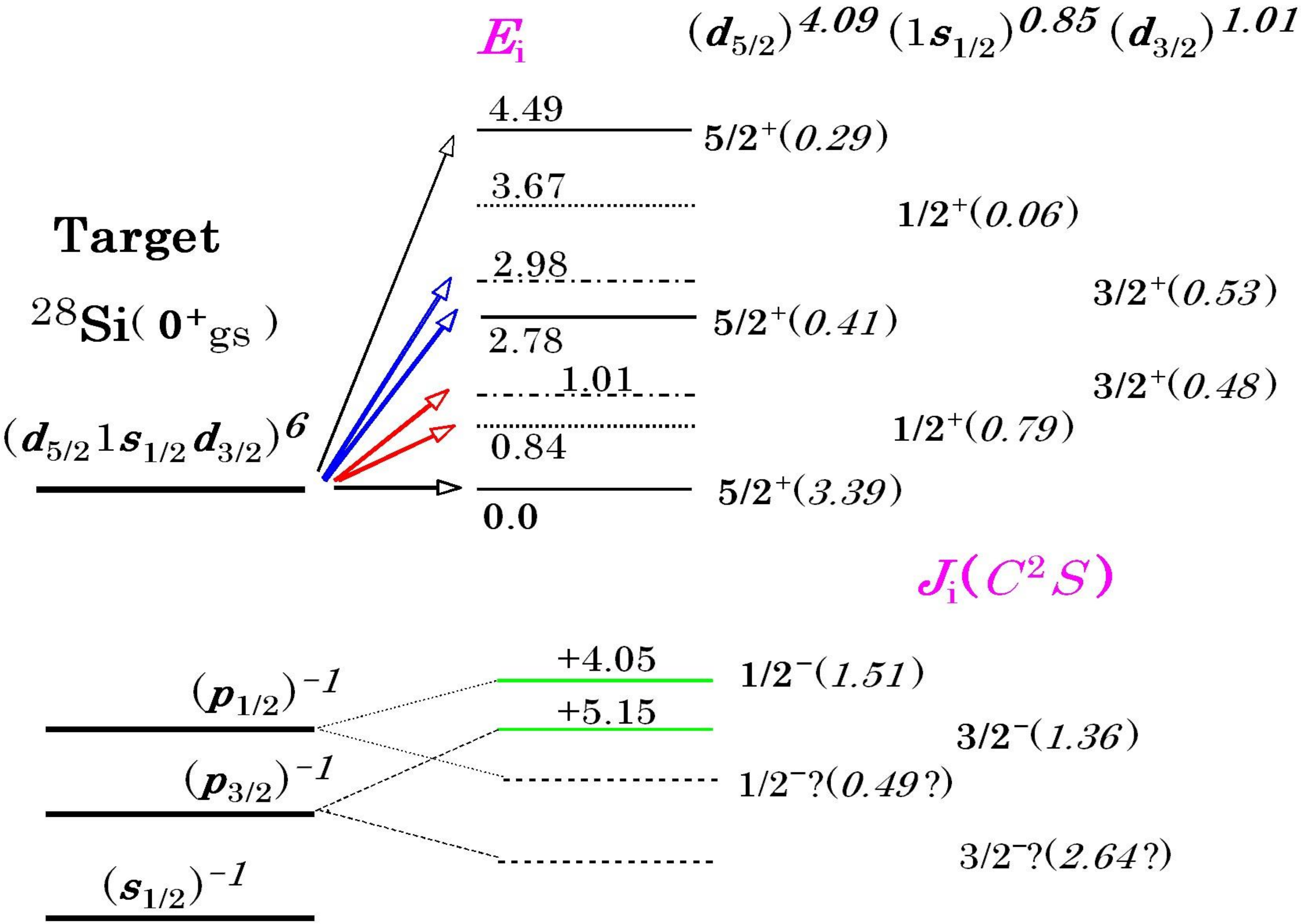
-- fragmentations when a proton is converted,

-- ^{27}Al core nuclear excitation

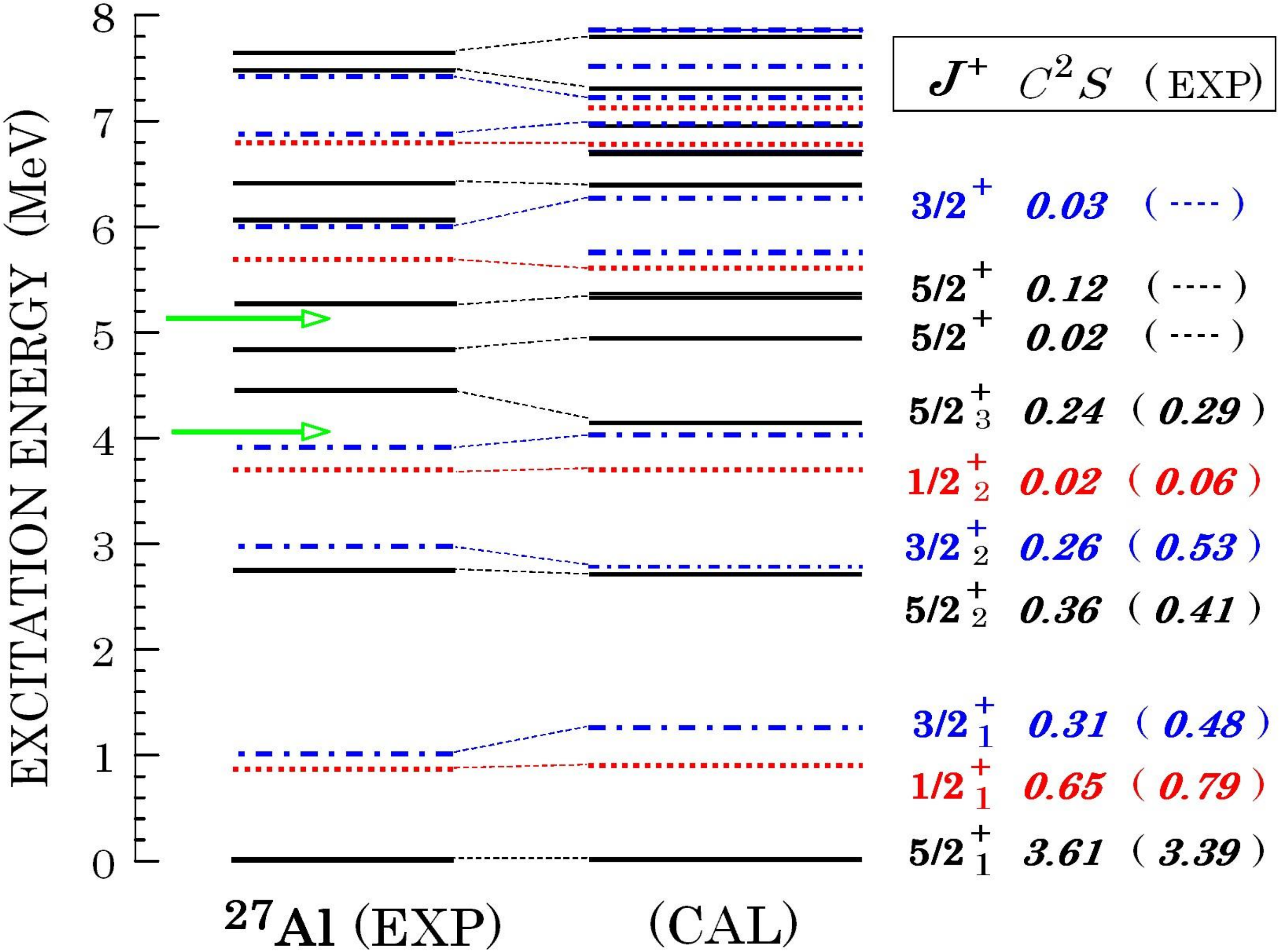
-- K^+ wave distortion effects

→ **Comparison with the $^{28}Si\ (e,e'K^+)$ exp.**

proton-state **fragmentations** should be taken into account *to be realistic*

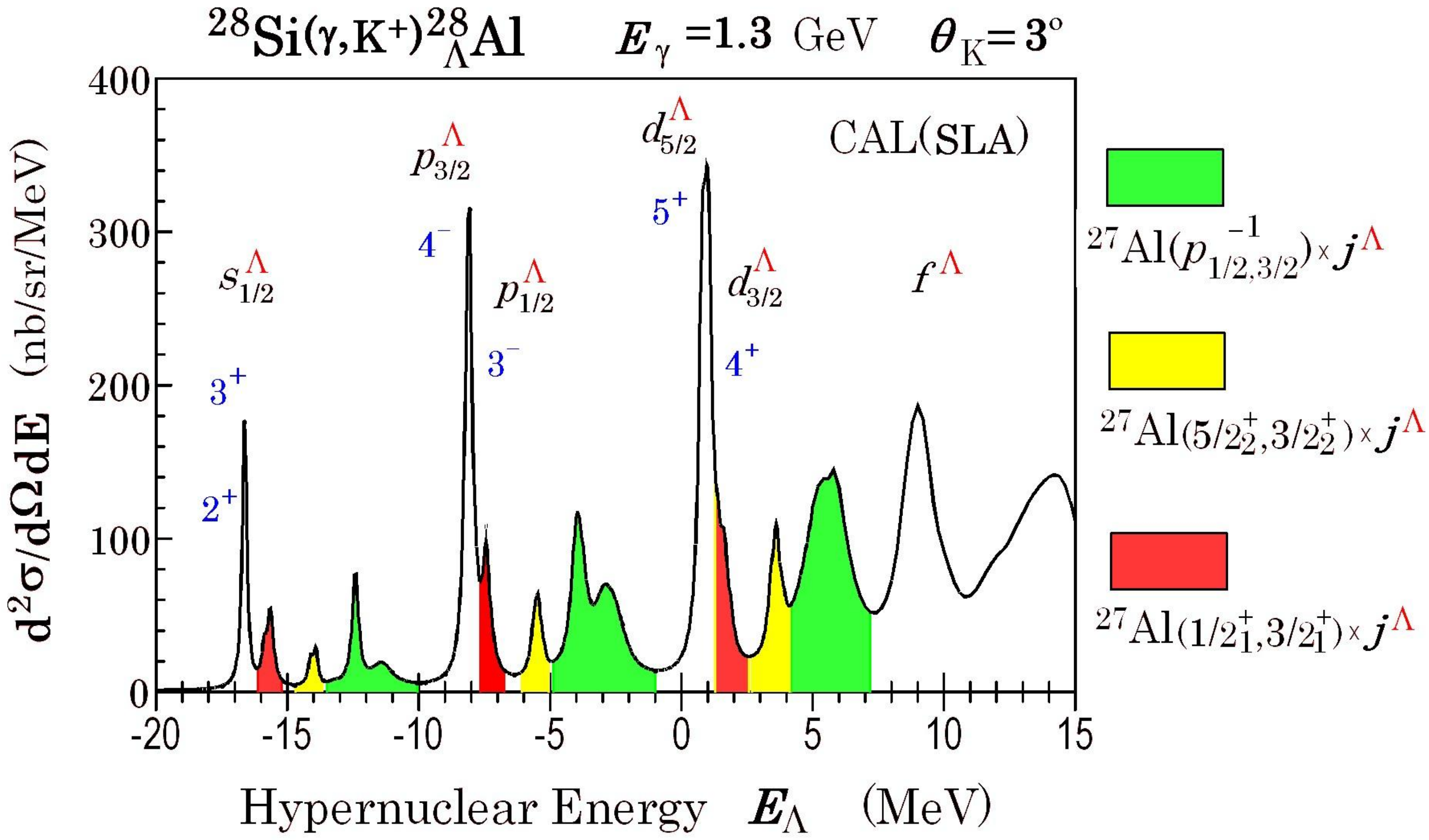


Proton pickup from $^{28}Si(0^+):(sd)^6 = (d_{5/2})^{4.1}(1s_{1/2})^{0.9}(d_{3/2})^{1.0}$



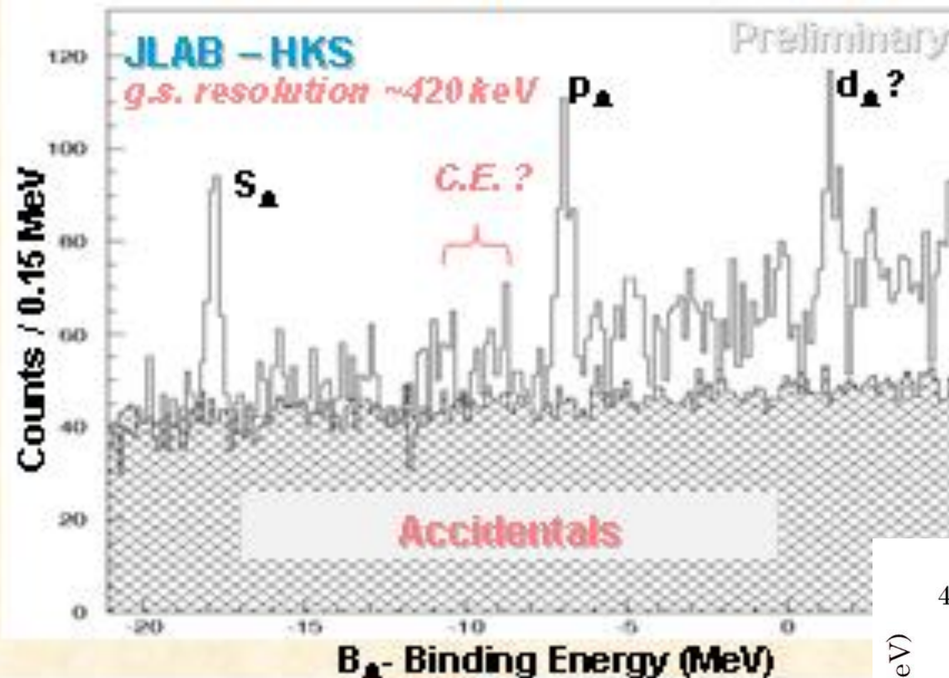
21

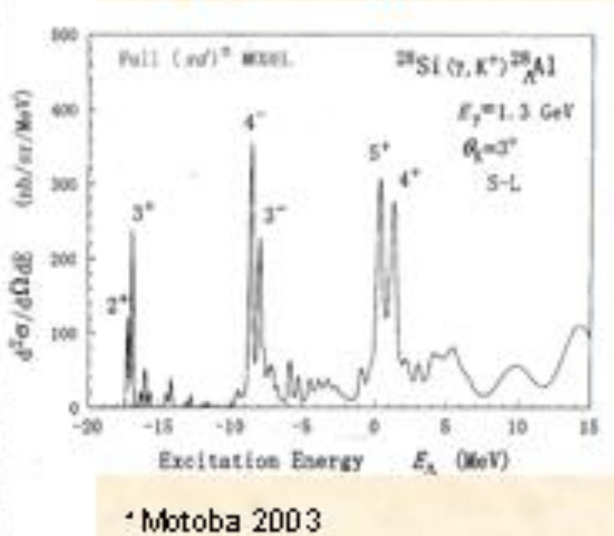
Peaks can be classified by the characters

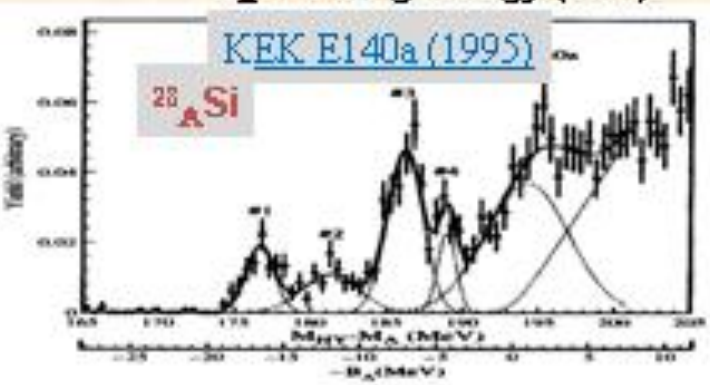


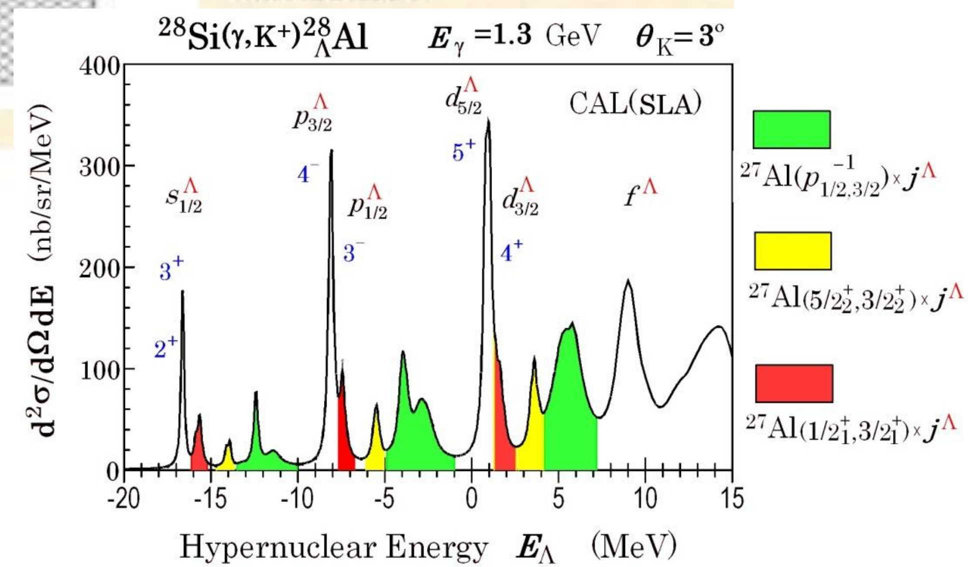
Major peak series : $[{}^{27}\mathrm{Al}(5/2^+_1) \times j^\Lambda]_J$ with $j^\Lambda = s, p, d, \ldots$

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









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

Peak energies: $^{28}_{\Lambda}$Si vs. $^{28}_{\Lambda}$Al

H.Hotchi et al, PRC 64(2001) vs. O.Hashimoto et al, NP A804(2008)

j Λ	^{28}Si(p^{+},K^{+})$^{28}_{\Lambda}$Si $E_{\Lambda}=-B_{\Lambda}$ (Ex)	^{28}Si(e,e'K^{+})$^{28}_{\Lambda}$Al (as read on the Sendai08 poster)	(γ,K^{+}) CAL
s	-16.6+-0.2 (GS)	-17.85 ?? (GS)	-16.6 (GS)
		-15.7 ? -13.0 ? -10.8 ?	-11.9+-0.4 (E_x=4.7)
p	-7.0+-0.2 (E_x=9.6)	- 6.88 +- ?? (E_x=11)	-8.1 (E_x=8.5)
	-4.3+-0.2 (E_x=12.4)		-5.6, -4.0
d	+1.0+-0.8 E_x=17.6)	+ 1.35 +/- (E_x=19.2)	+0.9 (E_x=17.5)

24

4. Extend to heavier nuclear Targets

^{52}Cr: $(f_{7/2})^4$ assumed

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

Well-separated series of peaks

due to large q and spin-flip dominance:

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

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

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

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

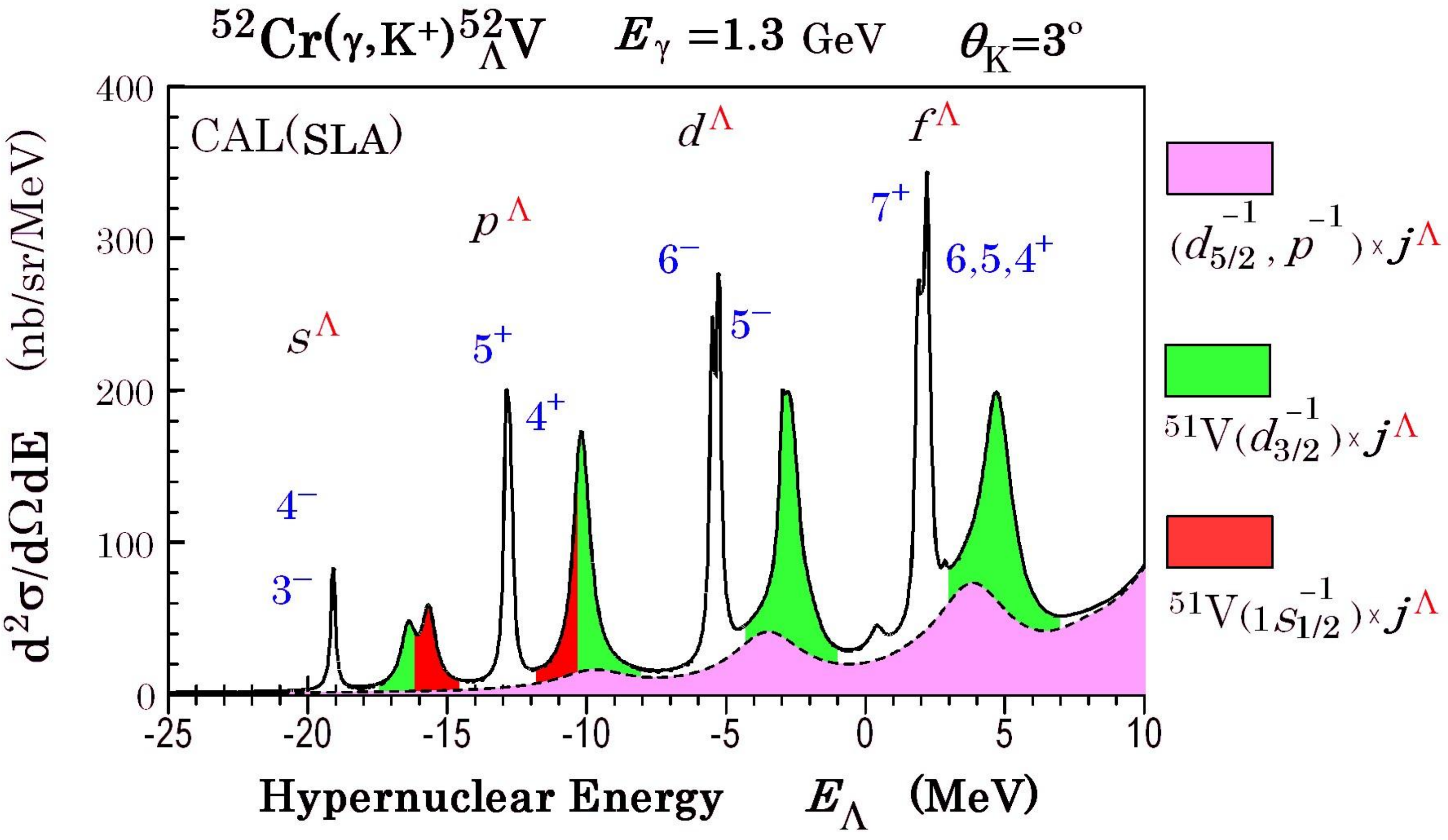
$[j_>^{-1}\, j_<^{\Lambda}]_J$ $J=j_>+j_<^{\Lambda}=l_{\rm p}+l_{\Lambda}=L_{\rm max}$ (natural parity)

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

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

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

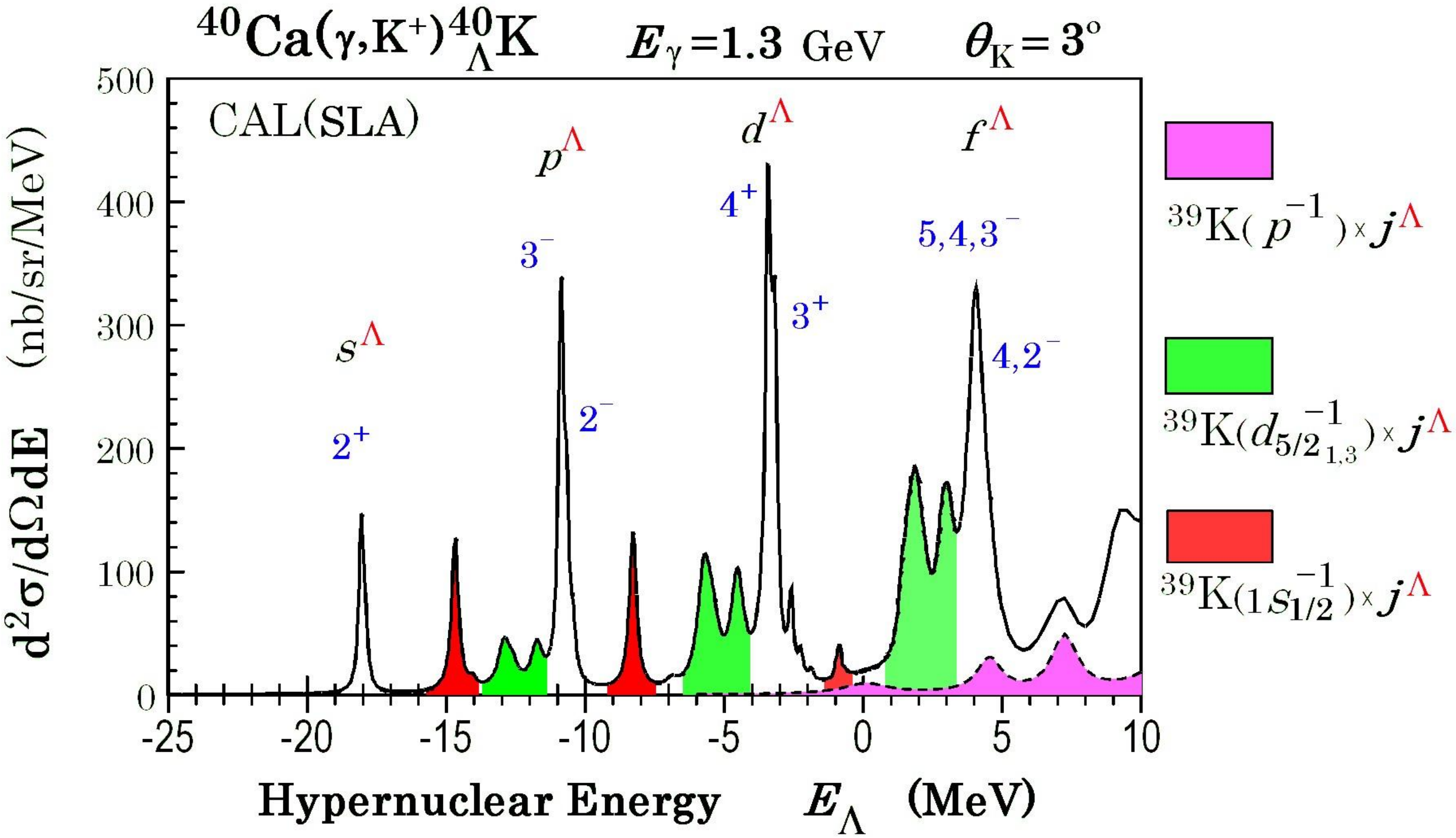
typical unnatural-parity high-spin states



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

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

6. SUMMARY

1) Basic properties of the $\gamma p \to \Lambda K^+$ process are discussed with typical models for the amplitudes:

------ spin-flip domiance, large q,

------ appreciable difference among theor. models (P).

2) Novel characteristics of photo/electroproduction of hypernuclei are clarified with the ^{28}Si target: $(d_{5/2})^{12}$ Model

$[j_>^{-1}\ j_>^{\Lambda}]$: $J_{max} = j_> + j_>^{\Lambda} = l_N + l_\Lambda + 1 = L_{max} + 1$ unnatural parity

$[j_>^{-1}\ j_<^{\Lambda}], [j_<^{-1}\ j_>^{\Lambda}]$: $J'_{max} = l_N + l_\Lambda = L_{max}$ orbitally streched

Selective excitation of high-spin states, providing a series of Λ orbits.

3) Realistic prediction for the ^{28}Si target was made. The calculation is in good agreement with the recent JLab exp. The predictions are made also for ^{40}Ca and ^{52}Cr.

4) Almost all predictions for the p-shell targets have been confirmed by the recent Jlab exp.(Hall A, C).

5) **Medium-mass hypernuclear production** by (e,e'K+) provide us with good opportunities in understanding the *details* of the hyperon motion in nuclear matter.(Λ-s.p.e. to establish "textbook", Rotation/Vib.-Λ coupling, Auger effect, μ_{Λ}, e_{eff} (Λ), etc)