Workshop on Future Prospects of Hadron Physics at J-PARC and Large Scale Computational Physics

February 9 – 11, 2012

Ibaraki Quantum Beam Research Center

Production of medium and heavy hypernuclei

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(Osaka E-C)

CONTENTS

1. Introduction / Basic motivations

production and decays of hypernuclei is

a window to disclose B-B interactions

2. Reaction spectroscopy

some theoretical predictions beyond p-shell

(e,e'K+) at JLab, (K-,π) and (π,K) at JPARC

3. Production of strangeness -2 hypernuclei

suggest (K-,K+) reaction on odd-Z sd-shell targets

4. Summary

$^{6}Li = 3p + 3n$

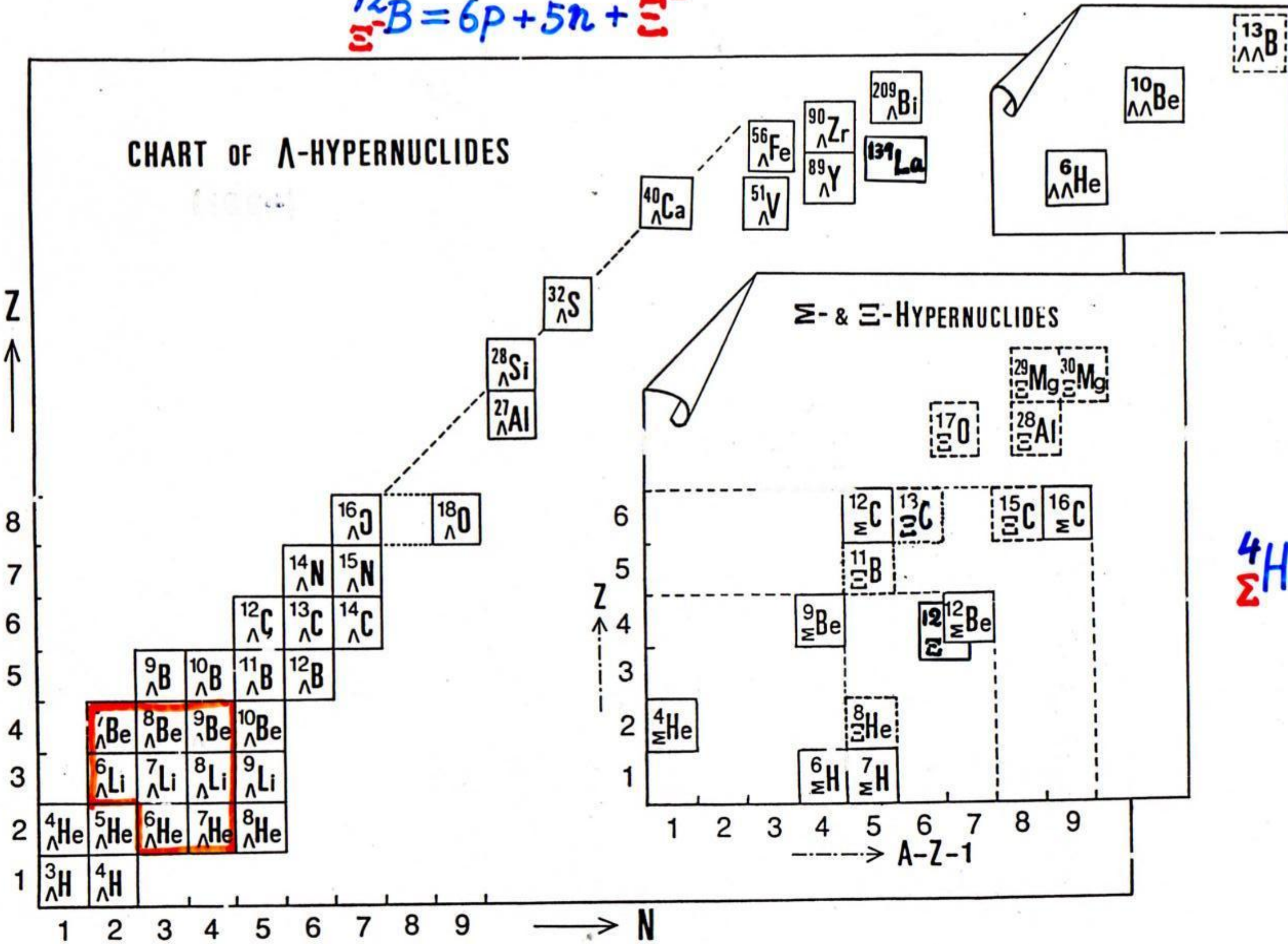
$^{7}_{\Lambda}Li = 3p + 3n + \Lambda$

$^{11}C = 6p + 5n$

$^{12}_{\Lambda}C = 6p + 5n + \Lambda$

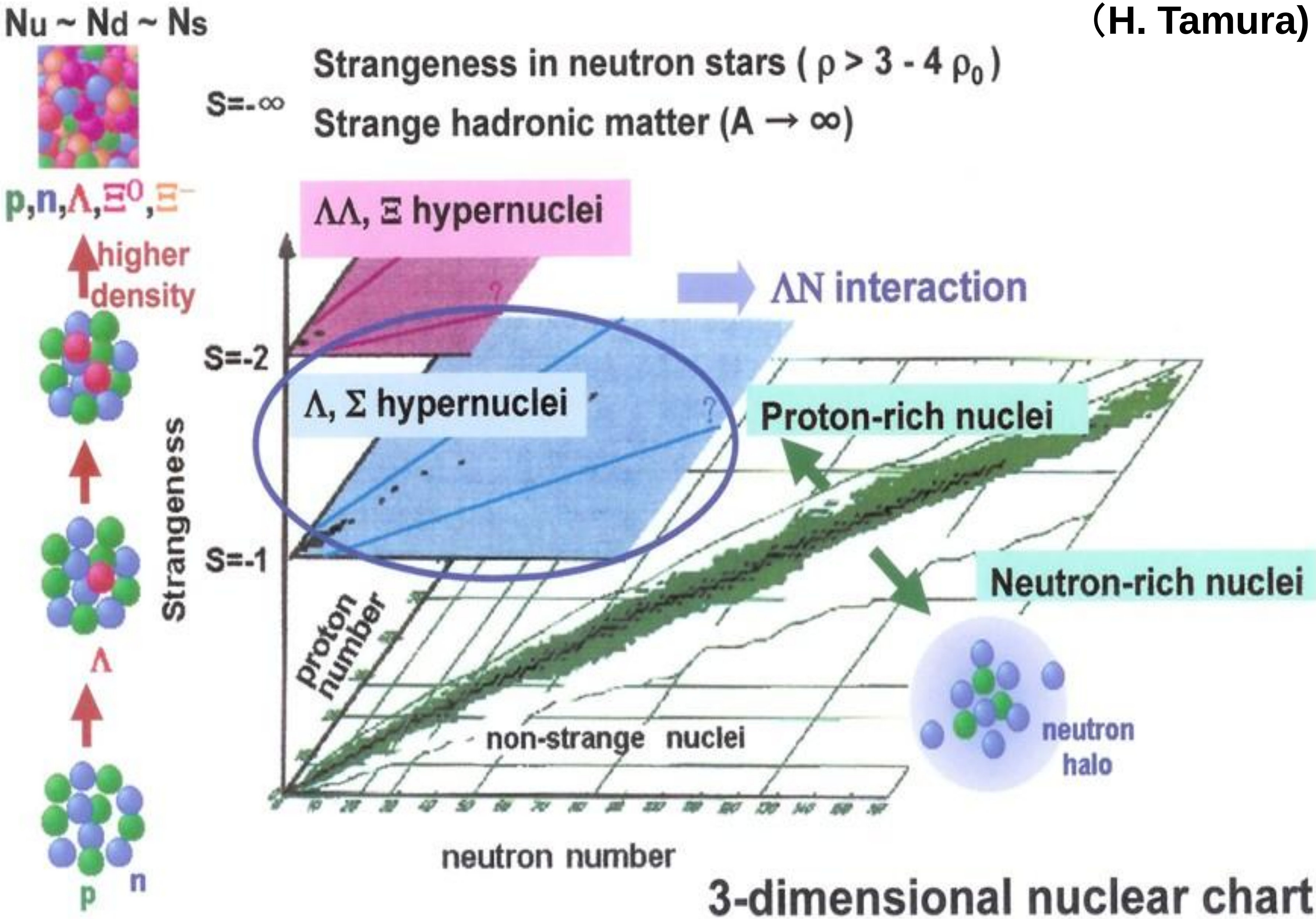
$^{12}_{\Xi^-}B = 6p + 5n + \Xi^-$

M-B-I, PTP Suppl. 81 (1986)
B-M-Z, Int.J. Mod.Phys.A5 (1990)



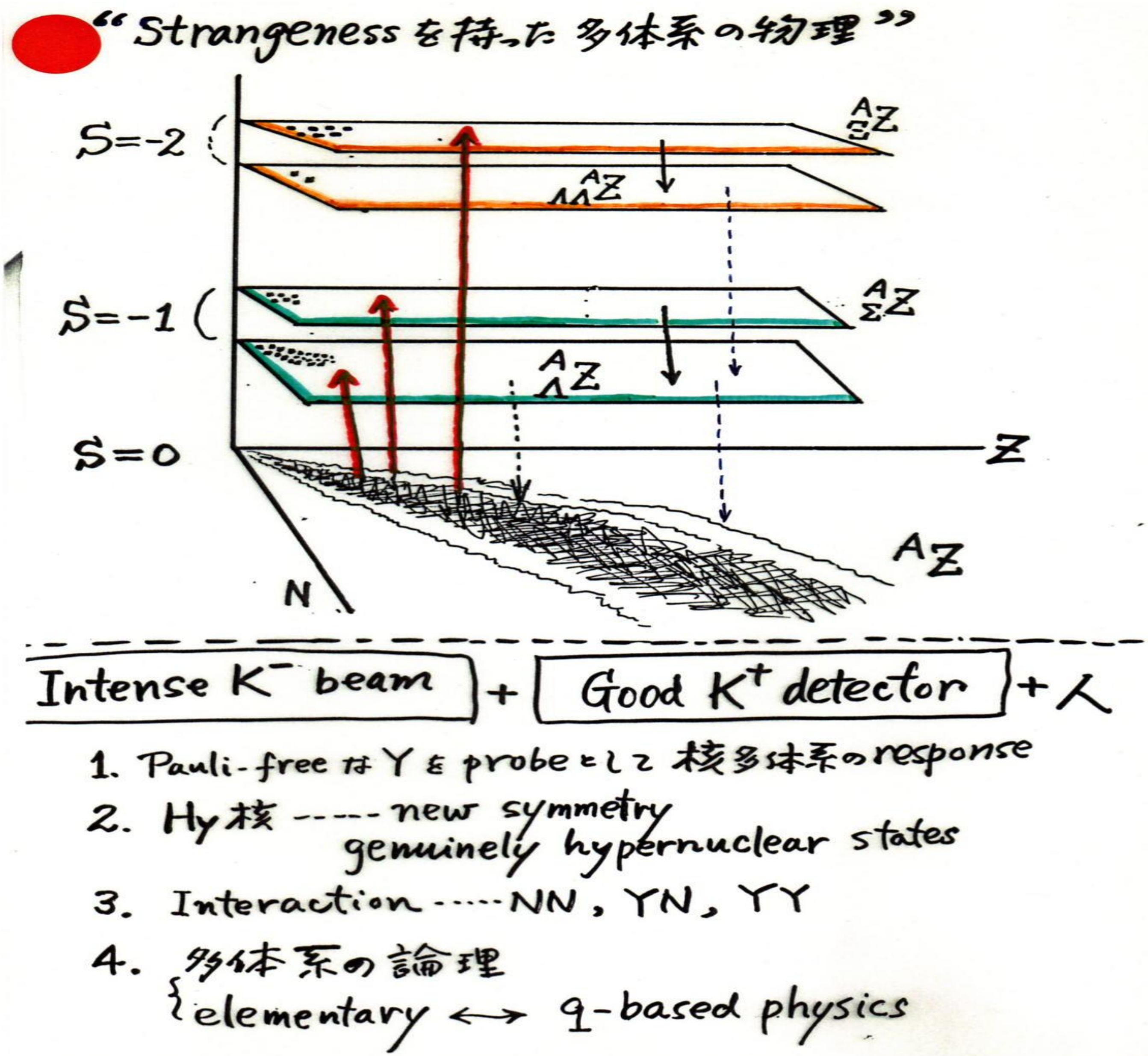
$^{4}_{\Sigma}He \begin{cases} 2p + n + \Sigma^0 & (^{3}He) \\ p + 2n + \Sigma^+ & (^{3}H) \end{cases}$

Fig. 1-1



(H. Tamura)
Nu ~ Nd ~ Ns
S=-∞
Strangeness in neutron stars (ρ > 3 - 4 ρ_0)
Strange hadronic matter (A → ∞)
p,n,Λ,Ξ^0,Ξ^-
higher density
ΛΛ, Ξ hypernuclei
ΛN interaction
S=-2
Λ, Σ hypernuclei
Proton-rich nuclei
Strangeness
S=-1
Neutron-rich nuclei
Λ
proton number
non-strange nuclei
neutron halo
p
n
neutron number
3-dimensional nuclear chart

Old slide for many-body system with *S*



First 3D-Chart

T.Motoba, Talk at ***Program on Big Hadron Project Physics,*** INS, U. Tokyo (1986), Genshikaku Kenkyu **32**, No.2. 97 (1987)

1. Introduction

Why medium-heavy hypernuclei ?

1) Λ single-particle energies: not well known

2) More chances of high-spin selectivity to see new aspects such as hyperon coupled with rotational and/or vibrational states.

3) Recent (e,e'K+) experiments encourage to go to sd- and fp-shell regions.

4) Expect to find "stable" Ξ-hypernuclear states, which leads to hyperon-mixing phenomena

Single-particle energies of Λ

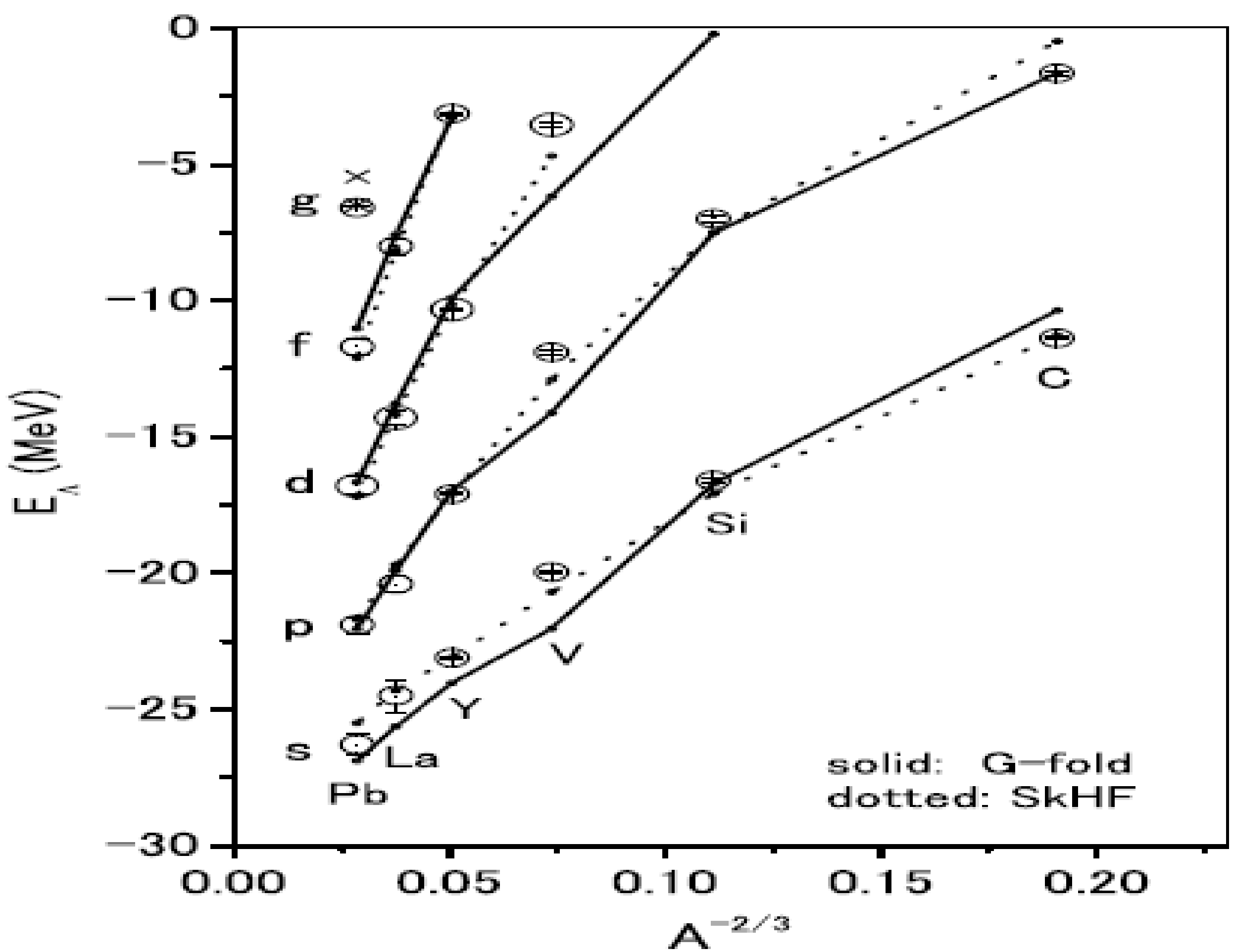


Fig. 1. Energy spectra of $^{13}_{\Lambda}$C, $^{28}_{\Lambda}$Si, $^{51}_{\Lambda}$V, $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La and $^{208}_{\Lambda}$Pb are given as a function of $A^{-2/3}$, A being mass numbers of core nuclei. Solid (dashed) lines show calculated values by the G-matrix folding model derived from ESC08a (the Skyrme-HF model). Open circles denote the experimental values taken from Ref. 17).

2.1 Developments in reaction spectroscopy of hypernuclear production

$$^{A}Z(J_i T_i \tau_i)(K^-, \pi^-)^{A}_{\Lambda}Z(J_f T_f \tau_f)$$

(π+,K+)
(γ, K+)
(K–,K+)

Theoretically reliable analyses take account of:

1. DW effects (DW vs. PW),
2. Microscopic treatment with elem. amplitudes,
3. Nuclear core excitation effects

(K^-,π^-)

(π^+,K^+)

played a great role of exciting high-spin series

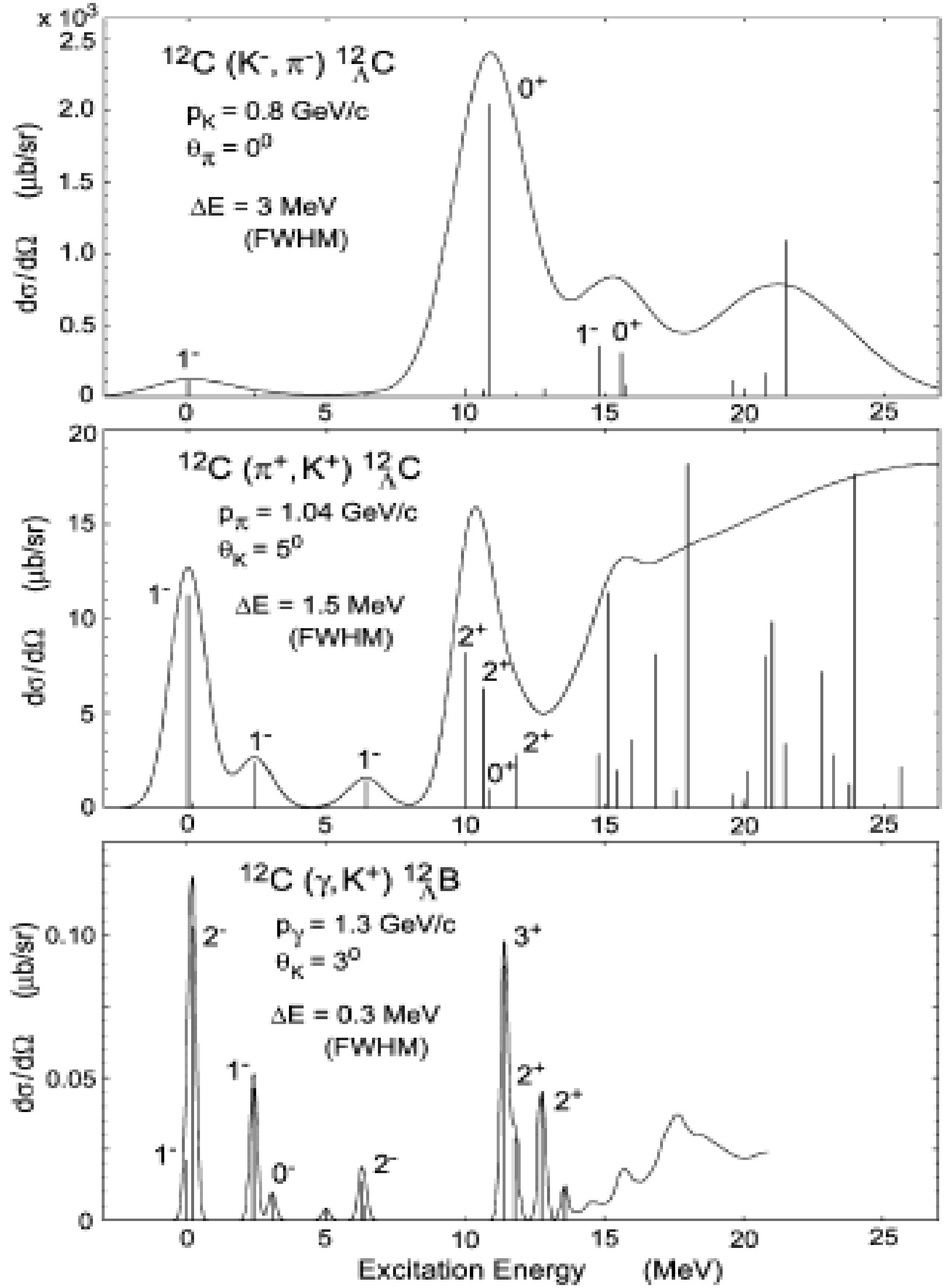
Γ = 1.5 MeV (best)

$(e,e'K^+)$, (γ, K^+)

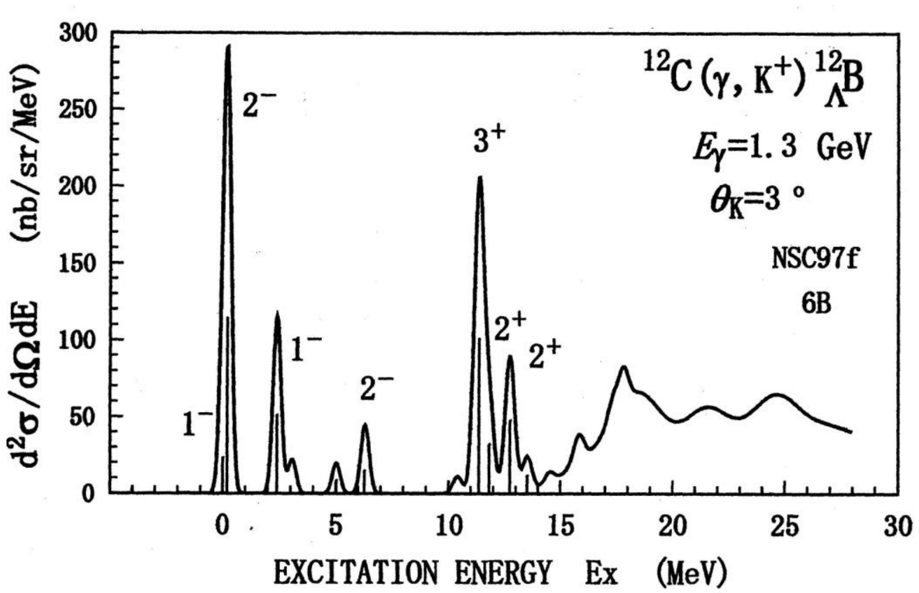
Motoba. Sotona, Itonaga, Prog.Theor.Phys.S.**117**(1994)

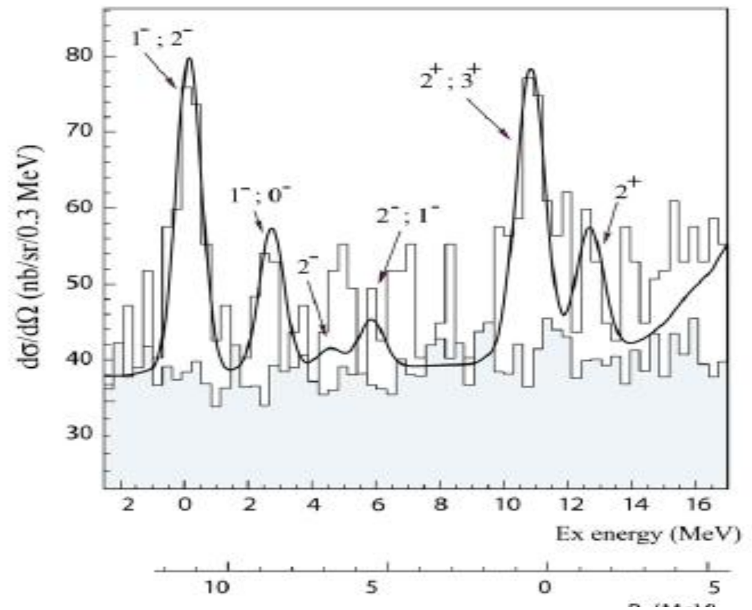
T.M. Mesons & Light Nuclei (2000) updated w/NSC97f.

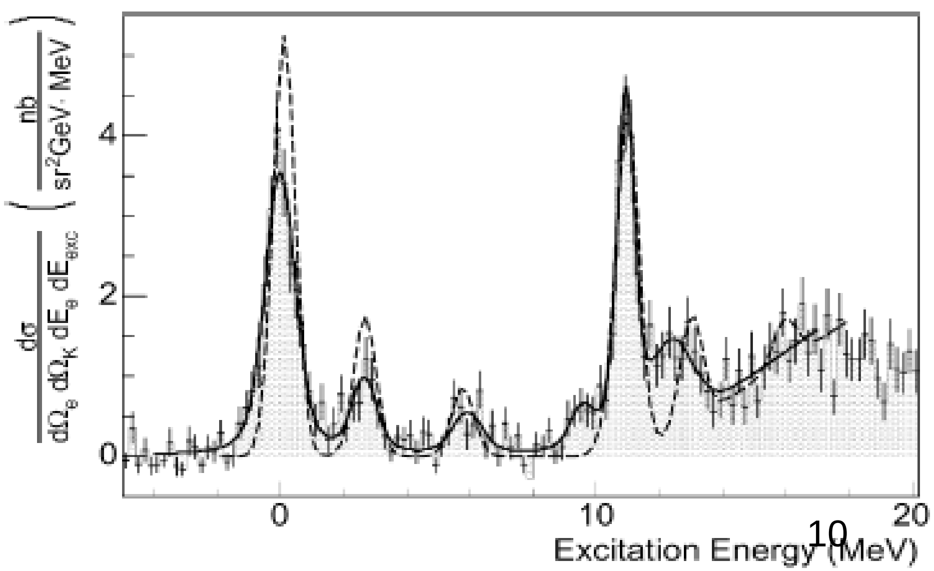
JLab Exp't : Γ = 0.5 MeV



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







Motoba. Sotona, Itonaga,
Prog.Theor.Phys.Sup.**117** (**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**

(e,e'K+) cross sections confirmed.

Table II. Comparison of the experimental energy levels and cross sections for $^{12}C(e, e'K^+)^{12}_{\Lambda}B$ with the theoretical estimates. The systematic experimental errors are not shown. Taken from Ref. 3).

E_x^{Exp} (MeV)	Width (MeV)	Cross section (nb/sr^2/GeV)	E_x^{Cal} (MeV)	Main structure $^{11}B[J_c] \otimes j^{\Lambda}$	J_f^{π}	Cross section (nb/sr^2/GeV)
0.0±0.03	1.15±0.18	4.48±0.29	0.0	$[3/2^-;\text{ g.s. }]\otimes s^{\Lambda}_{1/2}$	1^-	1.02
			0.14	$[3/2^-;\text{ g.s. }]\otimes s^{\Lambda}_{1/2}$	2^-	3.66
2.65±0.10	0.95±0.43	0.75±0.16	2.67	$[1/2^-; 2.12]\otimes s^{\Lambda}_{1/2}$	1^-	1.54
5.92±0.13	1.13±0.29	0.45±0.13	5.74	$[3/2^-; 5.02]\otimes s^{\Lambda}_{1/2}$	2^-	0.58
			5.85	$[3/2^-; 5.02]\otimes s^{\Lambda}_{1/2}$	1^-	0.18
9.54±0.16	0.93±0.46	0.63±0.20	−−	−−	–	–
10.93±0.03	0.67±0.15	3.42±0.50	10.48	$[3/2^-;\text{ g.s. }]\otimes p^{\Lambda}_{3/2}$	2^+	0.24
			10.52	$[3/2^-;\text{ g.s. }]\otimes p^{\Lambda}$	1^+	0.12
			10.98	$[3/2^-;\text{ g.s. }]\otimes p^{\Lambda}_{1/2}$	2^+	1.43
			11.05	$[3/2^-;\text{ g.s. }]\otimes p^{\Lambda}_{3/2}$	3^+	2.19
12.36±0.13	1.58±0.29	1.19±0.36	12.95	$[1/2^-; 2.12]\otimes p^{\Lambda}_{3/2}$	2^+	0.91
			13.05	$[1/2^-; 2.12]\otimes p^{\Lambda}$	1^+	0.27

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

(π+,K+)
PW vs. DW

(1)

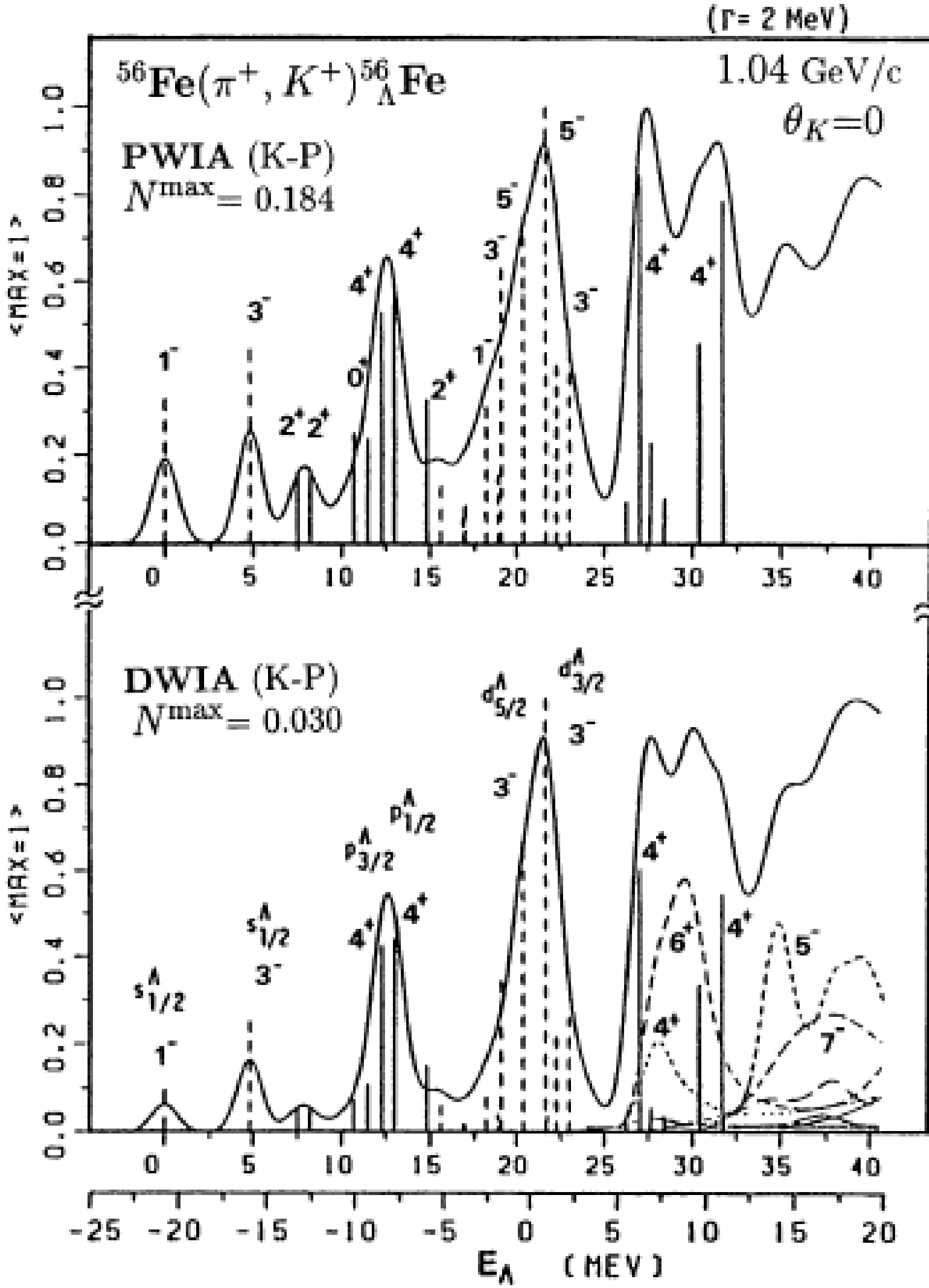
In a typical (π+,K+):

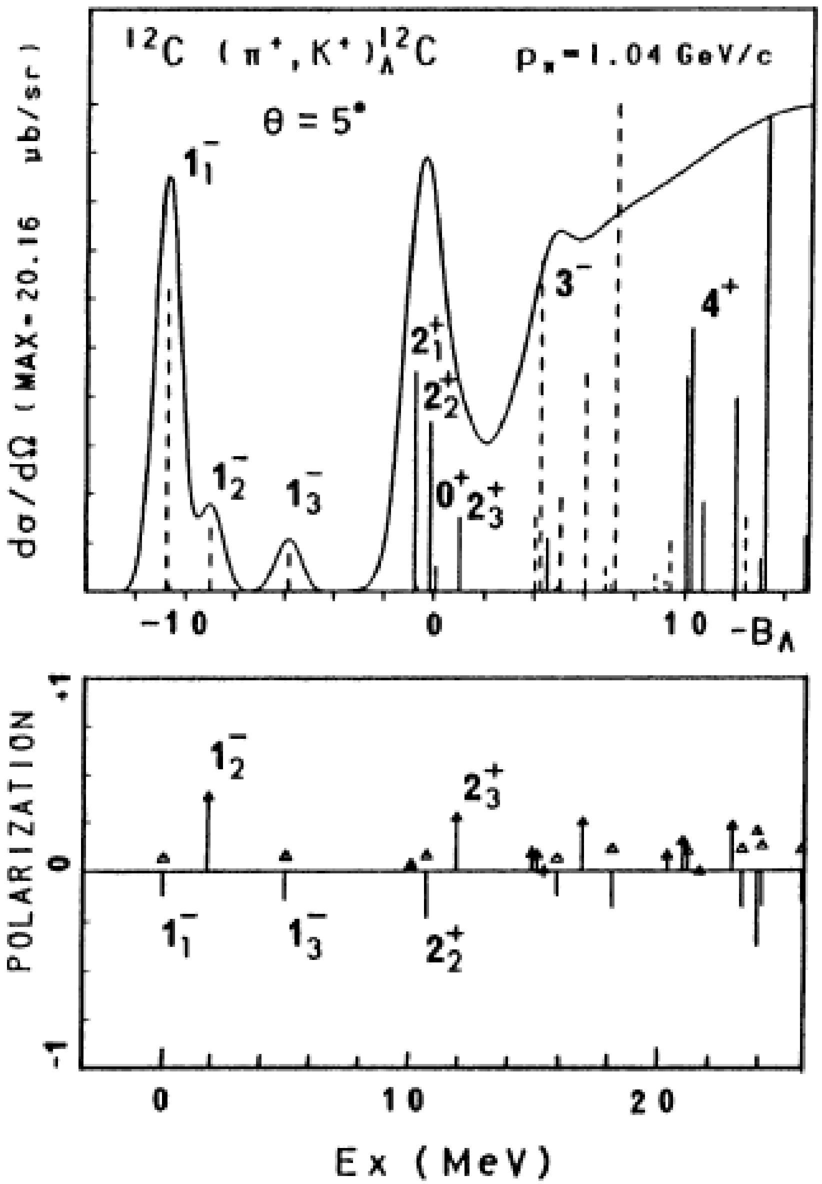
$\boldsymbol{N}_{\text{eff}}$ = **0.184** (PW)

0.030 (DW) 1/6

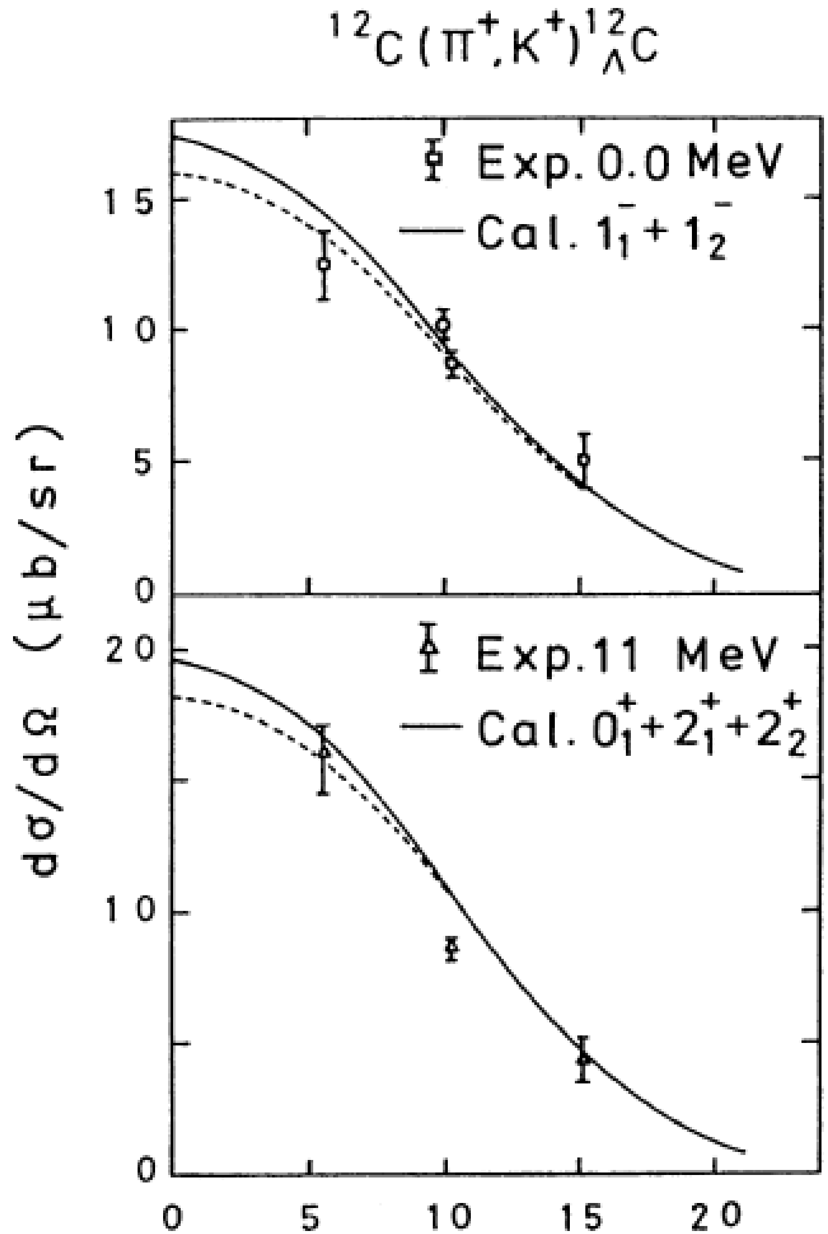
(2) XS to low-J states are much more reduced, resulting in the sharper peaks

(3) Interesting DW effect (mechanism)





$^{12}C\ (\pi^+, K^+)^{12}_{\Lambda}C$
p_π = 1.04 GeV/c
θ = 5°
dσ/dΩ (MAX = 20.16 μb/sr)
1_1^-
1_2^-
1_3^-
2_1^+
2_2^+
$0^+\ 2_3^+$
3^-
4^+
-10
0
10
$-B_\Lambda$
POLARIZATION
+1
0
-1
1_2^-
2_3^+
1_1^-
1_3^-
2_2^+
0
10
20
Ex (MeV)

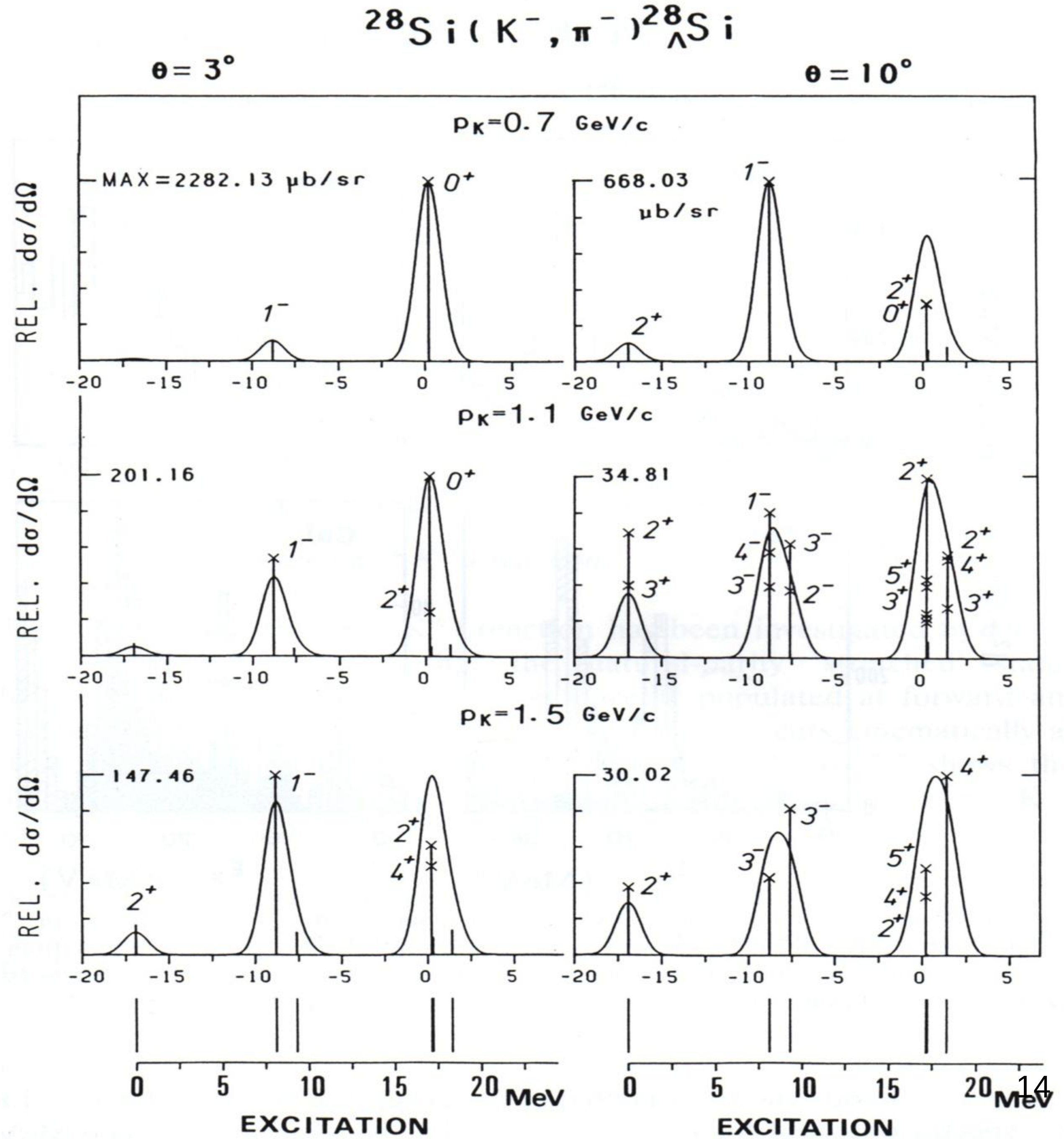


$^{12}C\ (\pi^+, K^+)^{12}_{\Lambda}C$
Exp. 0.0 MeV
Cal. $1_1^- + 1_2^-$
15
10
5
0
dσ/dΩ (μb/sr)
Exp. 11 MeV
Cal. $0_1^+ + 2_1^+ + 2_2^+$
20
10
0
0
5
10
15
20

(K-,π-) on 28Si at p=0.7

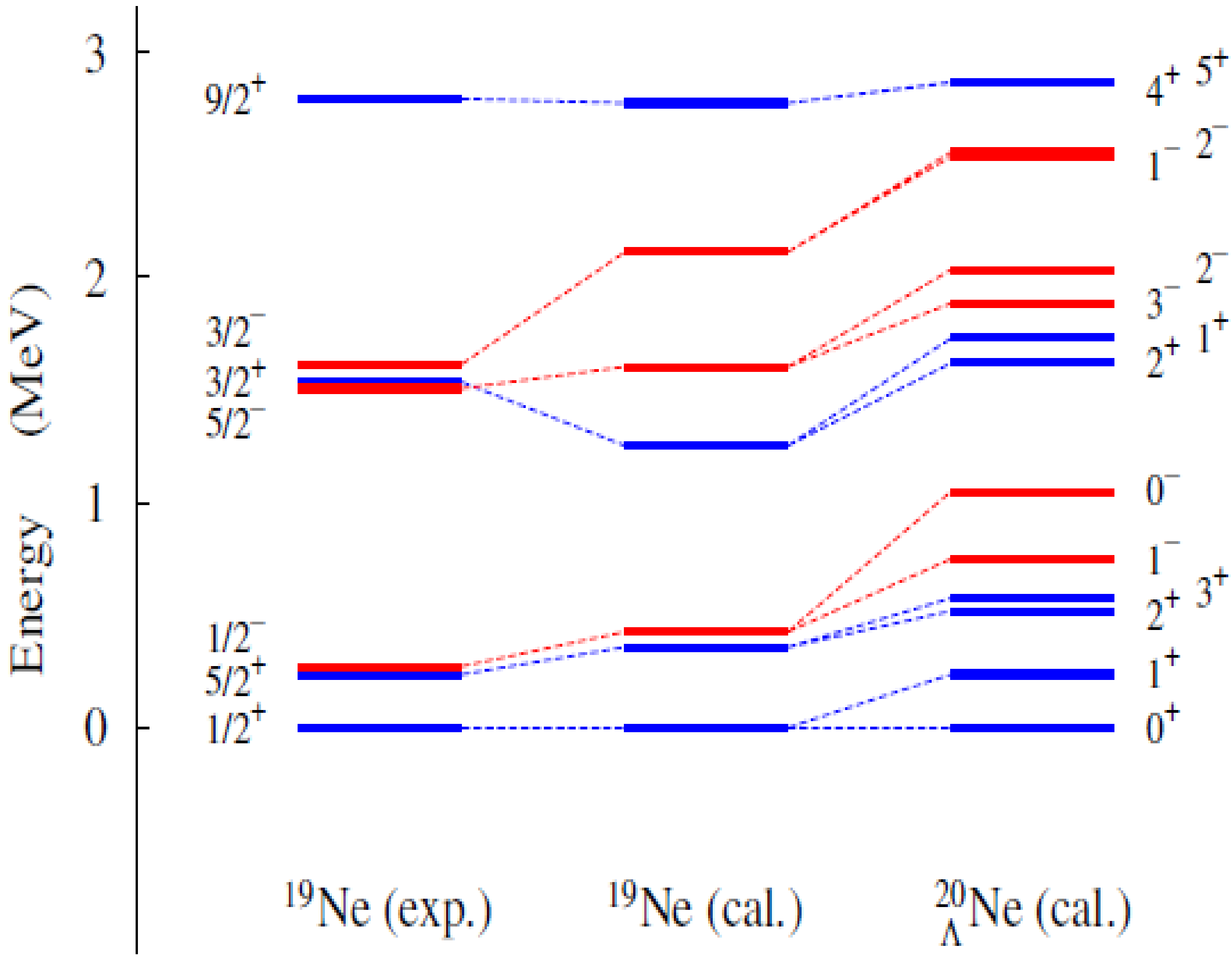
p=1.1

p=1.5 GeV/c



Numerical Results : Low-lying energy levels of $^{20}_{\Lambda}$Ne and ^{19}Ne

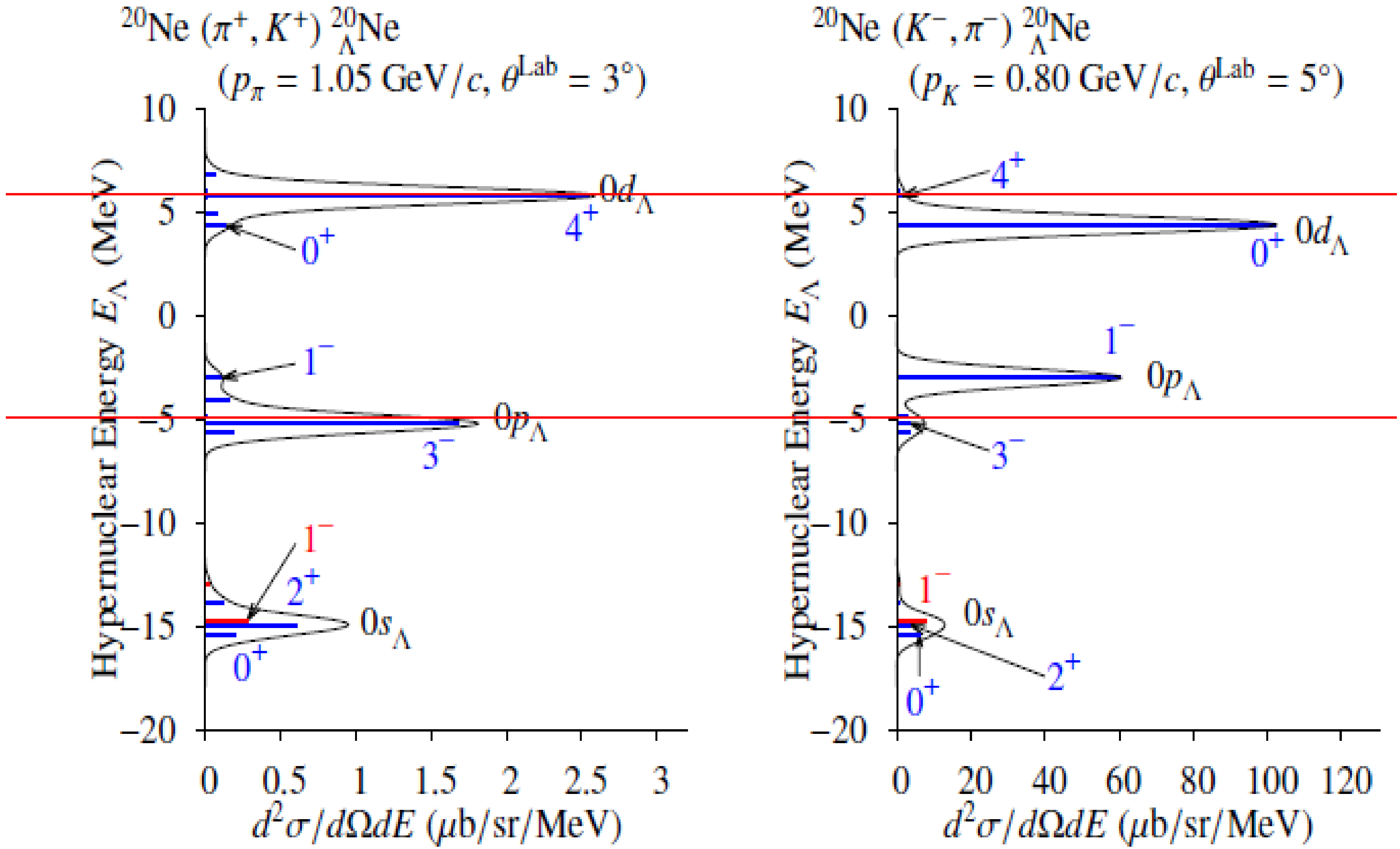
(by Umeya)



0^- : 1.050 MeV
1^- : 0.751 MeV
3^+ : 0.578 MeV
2^+ : 0.519 MeV
1^+ : 0.239 MeV
0^+ : 0.000 MeV

Numerical Results : Production cross sections

(by Umeya)



(K-,p) at p~1.1 and 1.5 GeV/c expected to be done at J-PARC

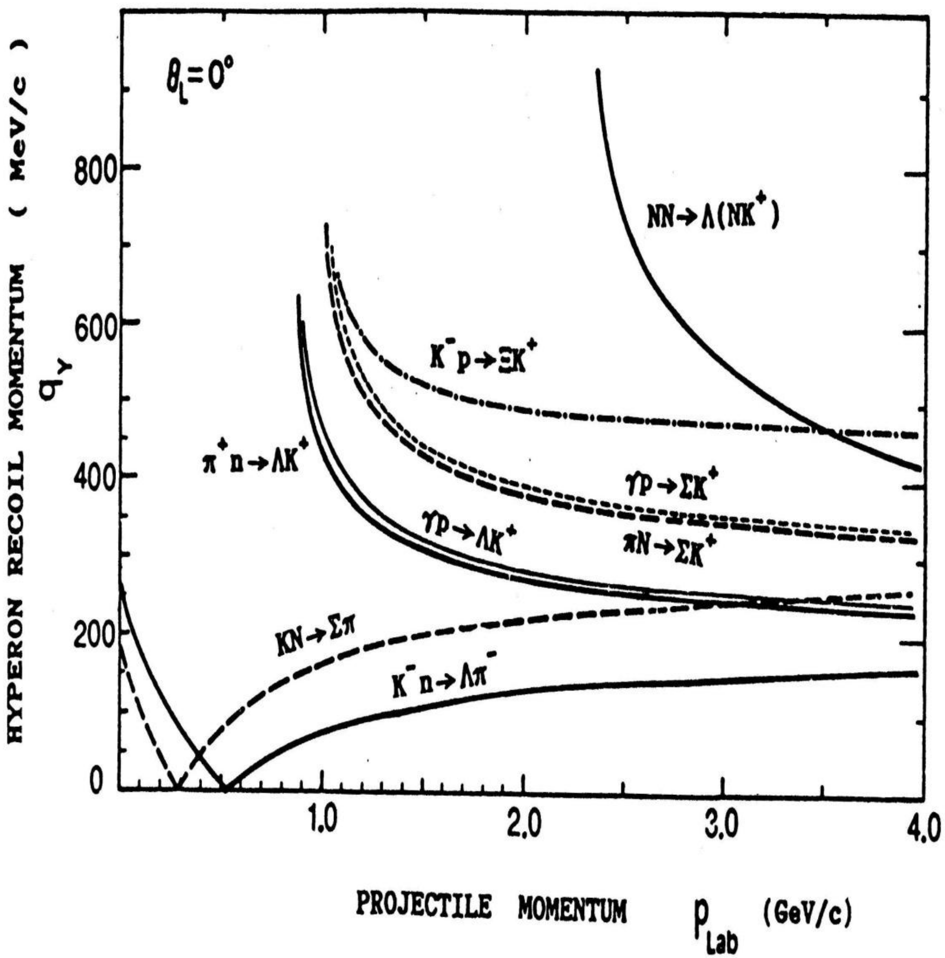
- can produce polarized hypernuclei
- Not only "substitutional (ΔJ=0)" states but also other states are excited at the same time.
- provide chances to see interplays between Λ and collective motions of nuclear core

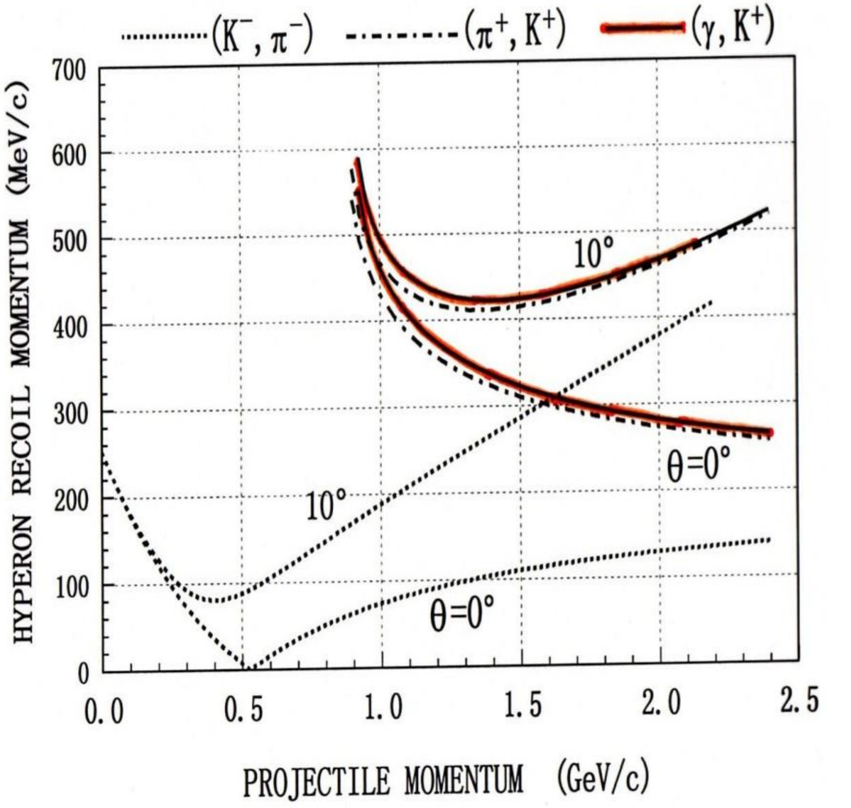
2.2 Electro/photo-production of sd-shell ~ hypernuclei

(some cases for sd-shell: already done at Jlab, and expected to be done at MAMI)

- Microscopic based on elem. ampl.
- DW: solution of the Klein-Gordon eq.
- Emphasize the importance of taking account of nuclear core excitation effects

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





q_Λ**=350-420** MeV/c at Eγ=1.3 GeV

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

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

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

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:

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

$$g_0 = a_1 ,$$

Spin-flip interaction are dominant

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

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

Realistic prediction for $^{28}Si\ (\gamma,K^{+})\ _{\Lambda}^{28}Al$ with full sd-wf

By fully taking account of

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

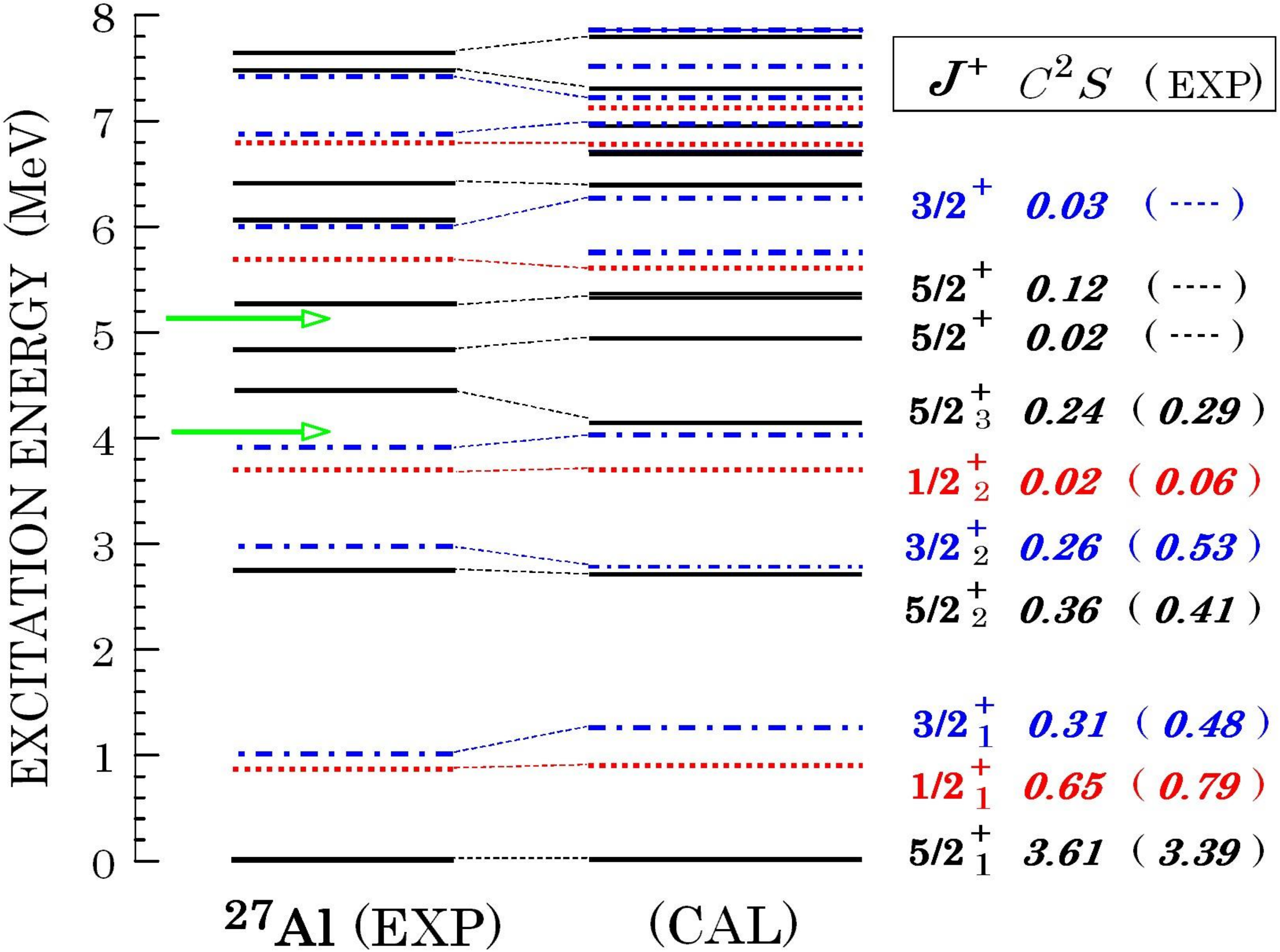
-- fragmentations when a proton is converted,

-- ^{27}Al core nuclear excitation

-- K^{+} wave distortion effects

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

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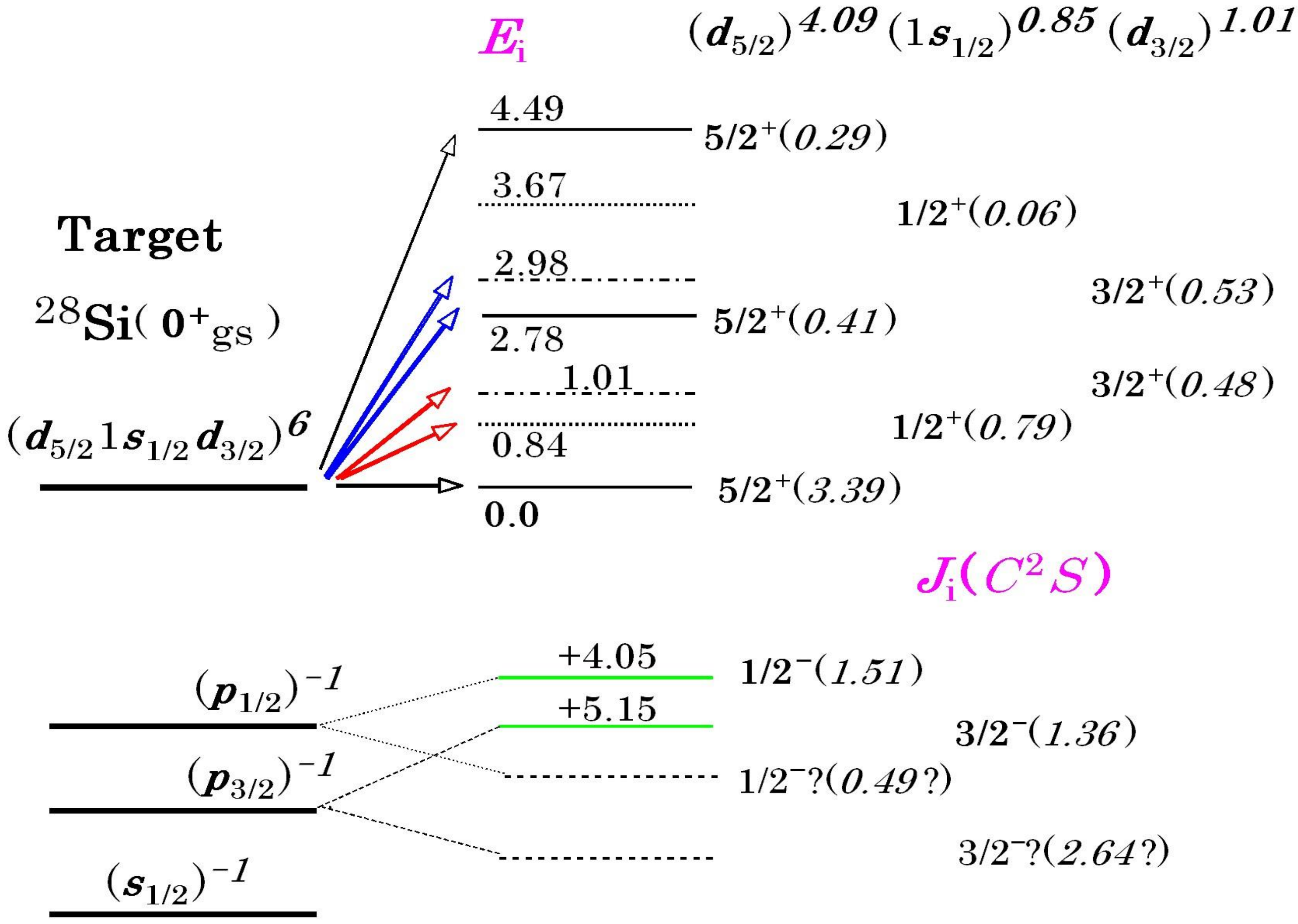
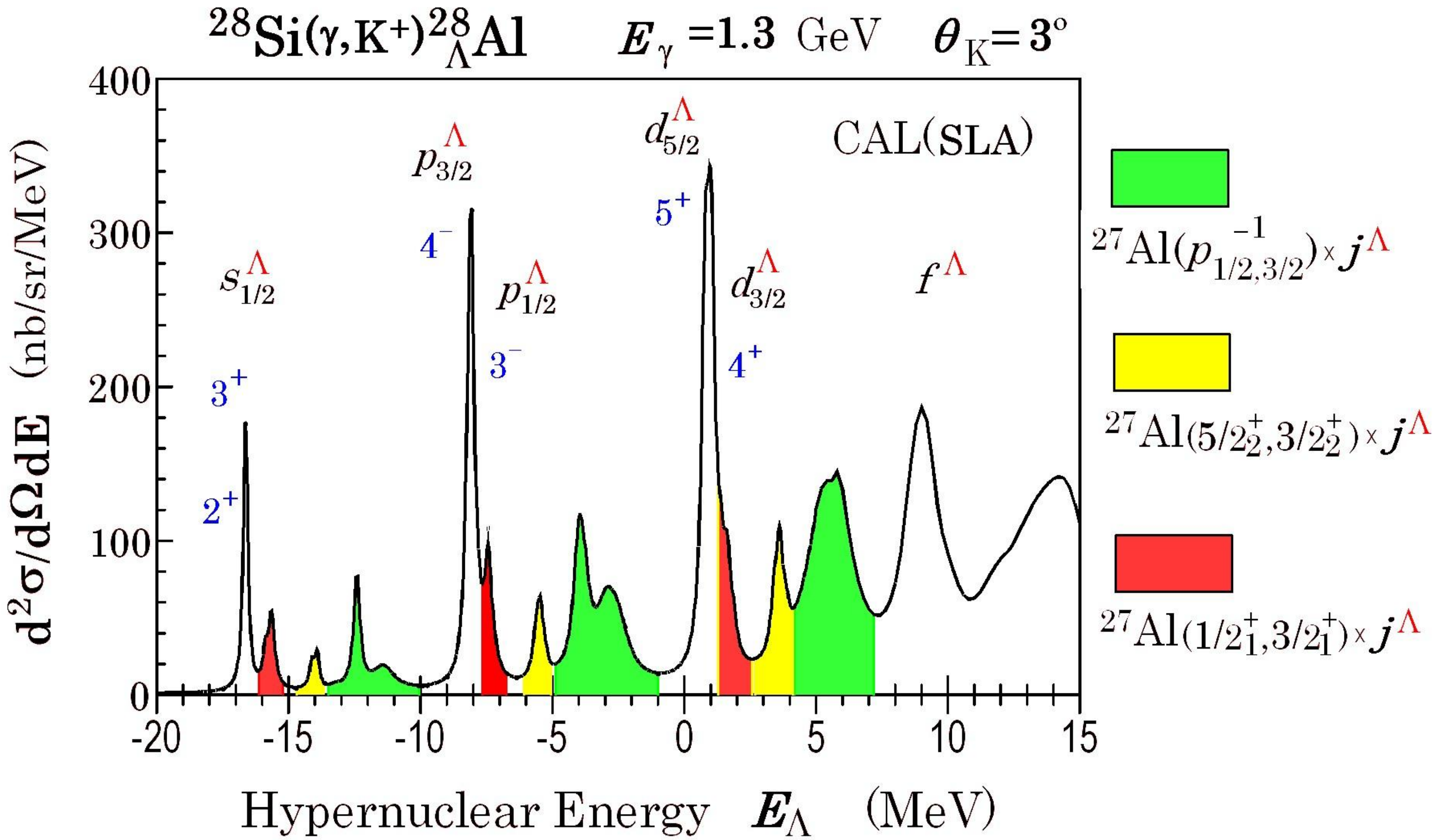
proton-state **fragmentations** should be taken into account *to be realistic*

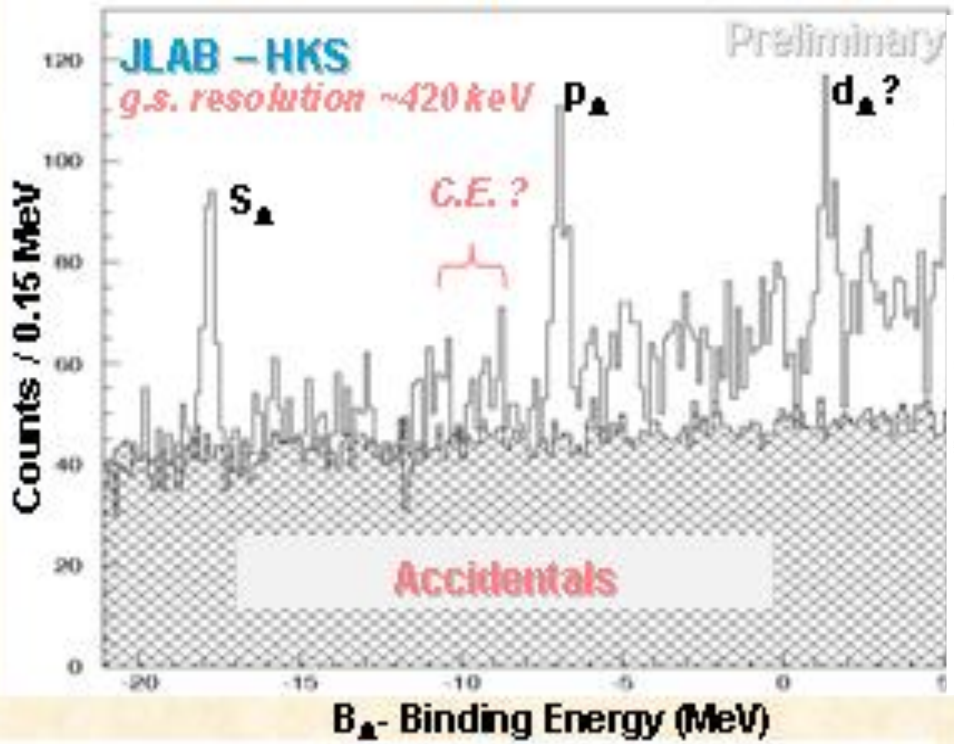


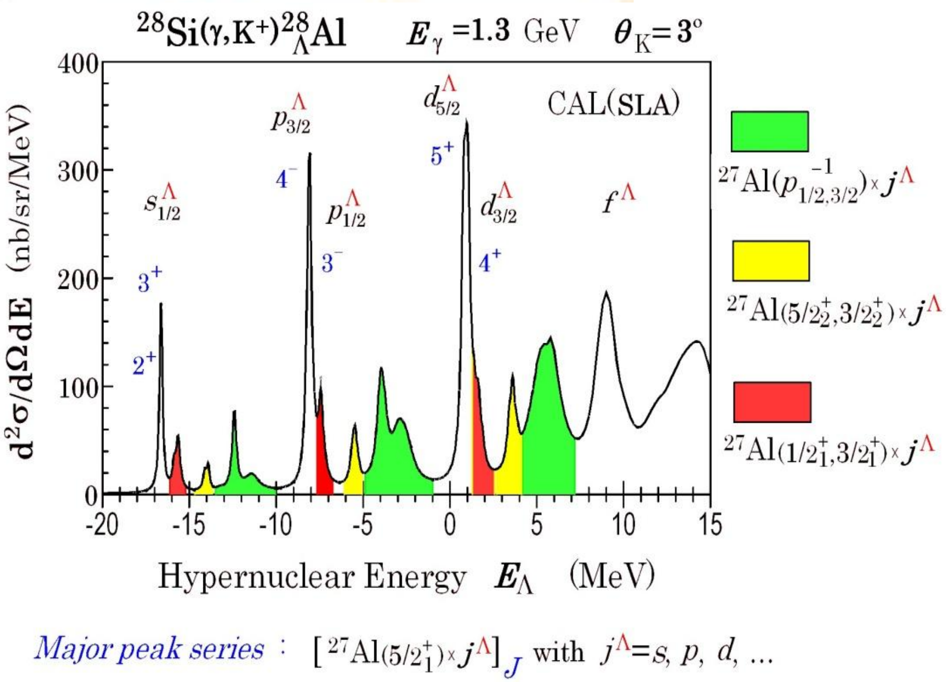
Peaks can be classified by the characters

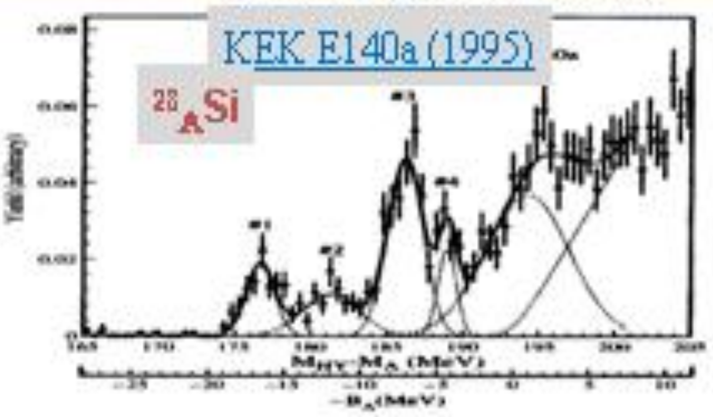


Major peak series : $[\,^{27}Al(5/2^+_1) \times j^{\Lambda}]_J$ with $j^{\Lambda}= s, p, d, \ldots$

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







Far better energy resolution!

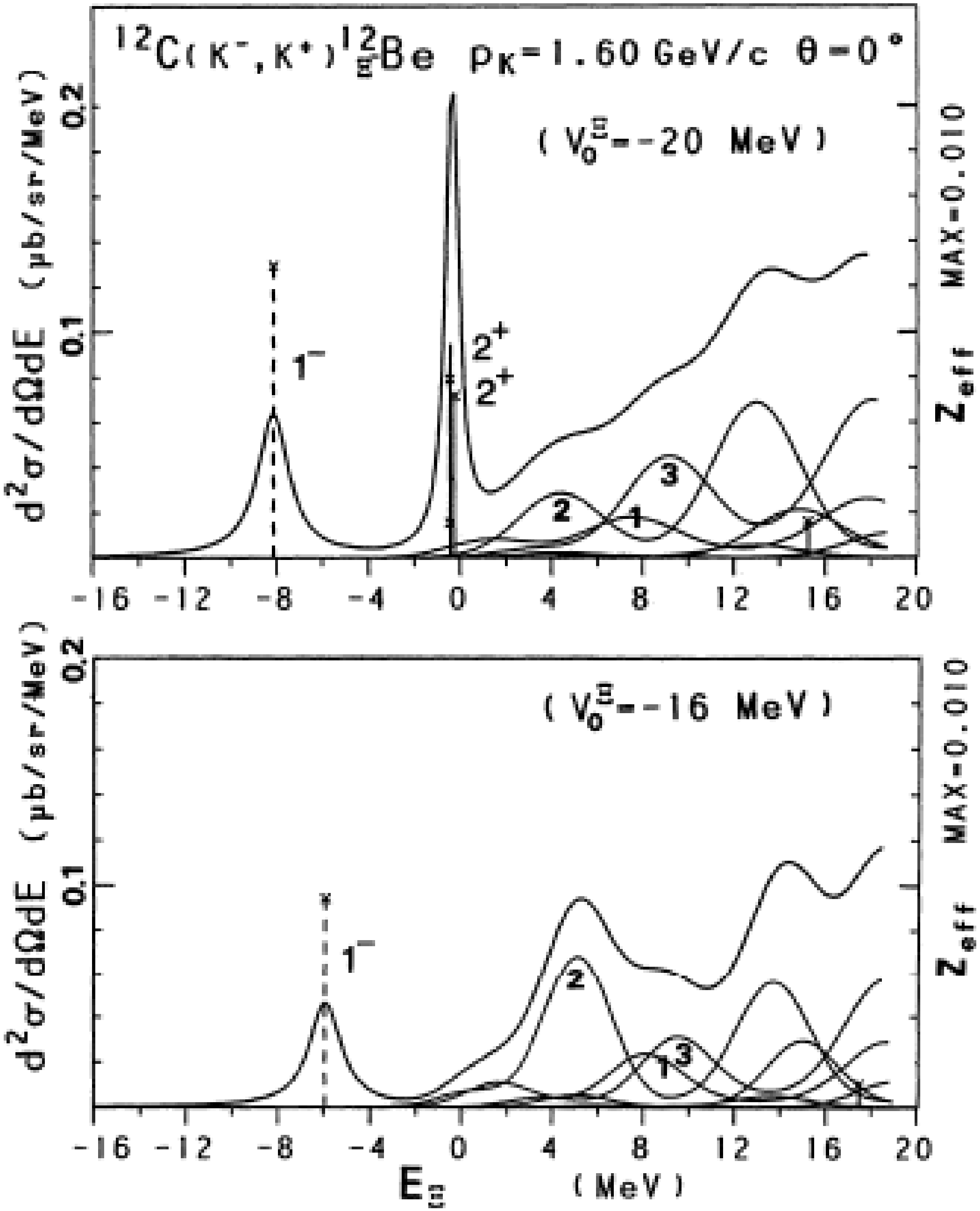
In comaprison with
(π+,K+) experiment from KEK

3. Production of Ξ-hypernuclei (and ΛΛ-hypernuclei)

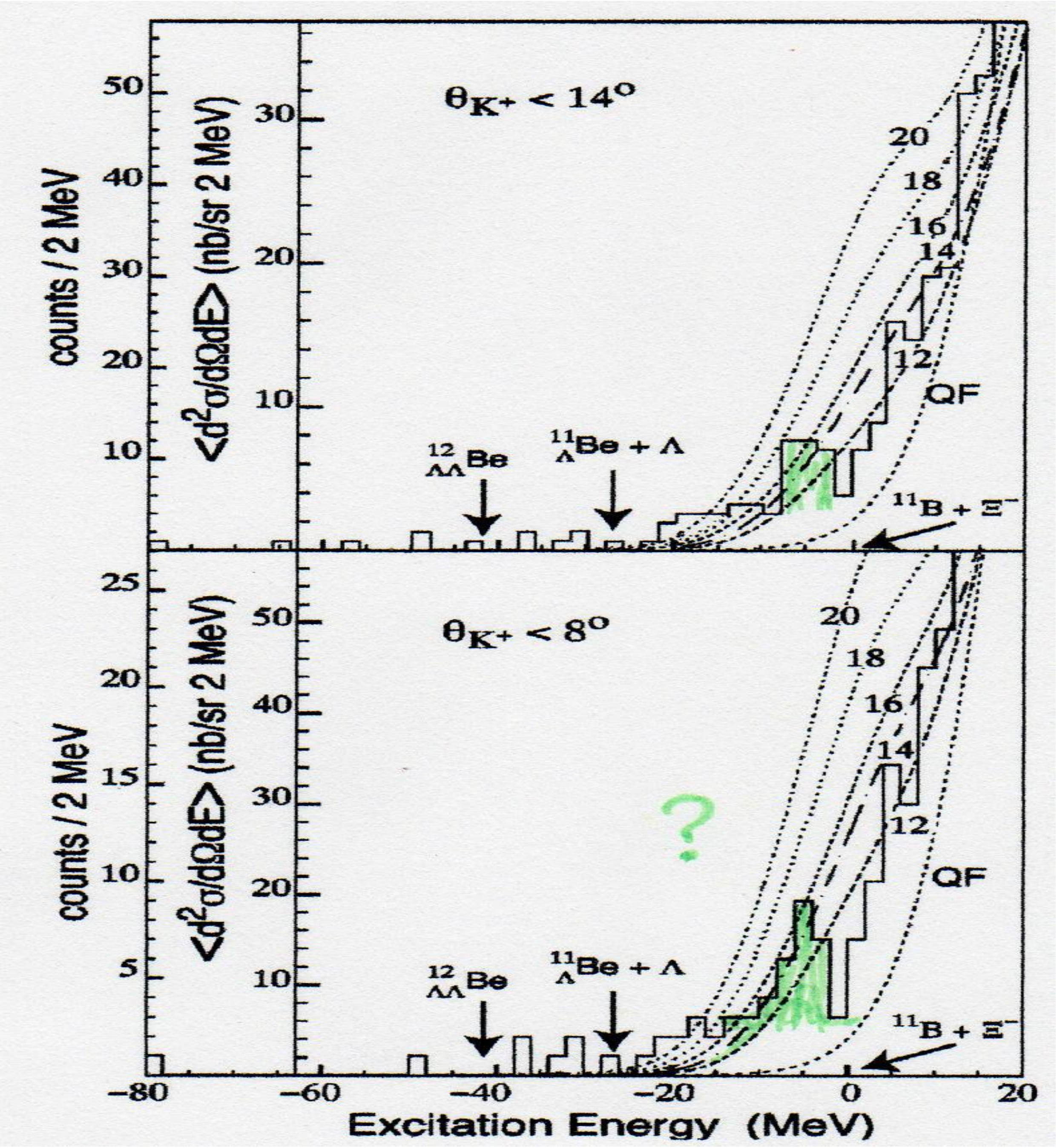
-The similar theoretical framework has been applied to (K-,K+) reaction on 12C.

- DW: solution of the Klein-Gordon eq.

-taking account of nuclear core excitation effects



Arbitrary smearing widths are used in these figures



BNL-E885

P. Khaustov et al, PRC 61 (2000)

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

Suggesting:

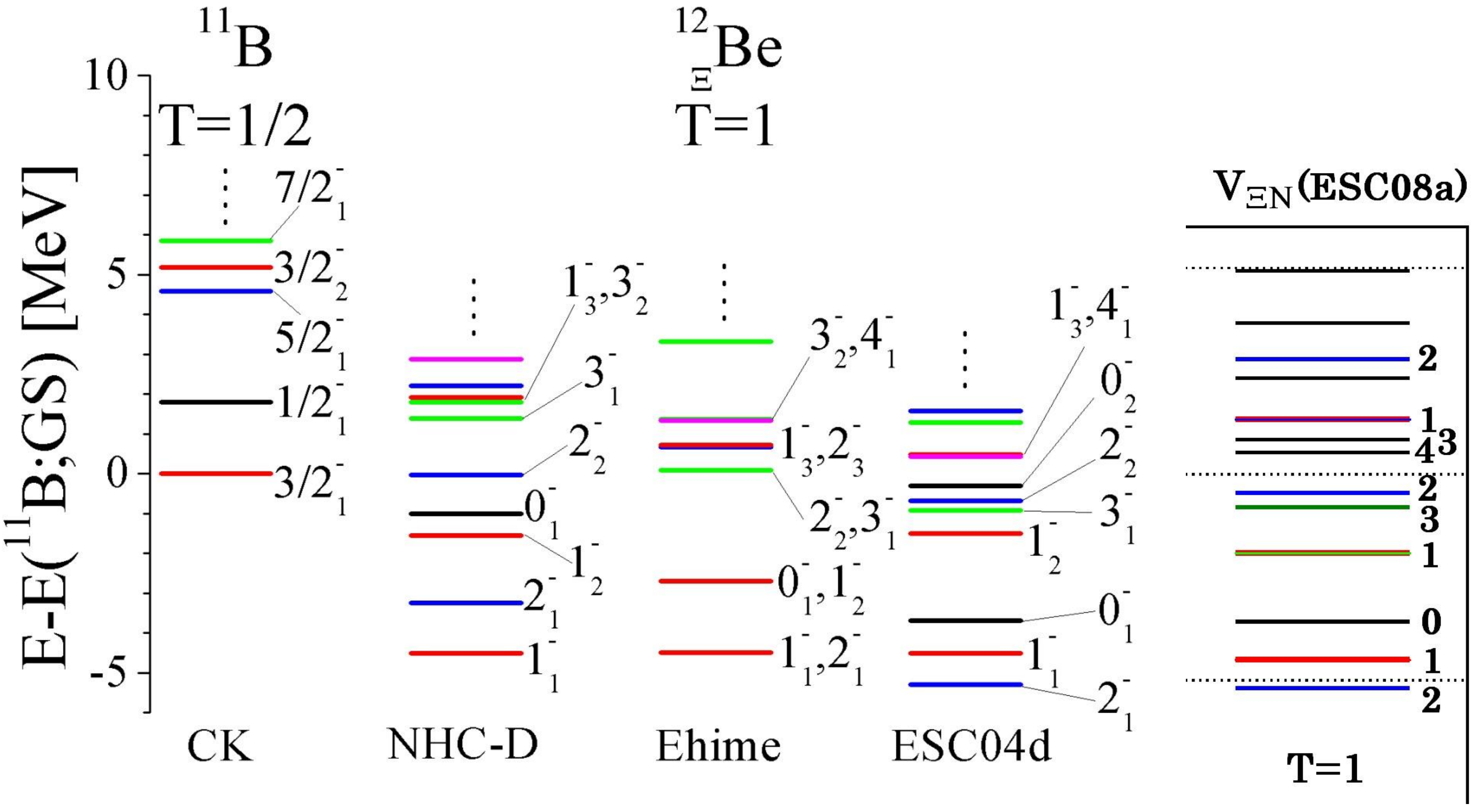
only WS-pot. depth:

U=12-14 MeV or less.

"shallow"

Reference position of J=1-(T=1) states.

The relative positions of J_n show the different σ.σ interaction nature of $V_{\Xi N}$.



Ξ-N interactions used in Shell Model

Comparison in the form of $V = -V_0 + \Delta(\sigma.\sigma)$

		V_0	Δ	Δ/V_0
$N\Xi$(ESC04d)	T=0	4.98	-15.81	-3.18
	T=1	0.30	-2.96	-9.88
$N\Xi$(NHC-D)	T=0	2.14	4.75	2.23
	T=1	1.55	0.79	0.51
$N\Lambda$(NSC97f)	T=1/2	1.05	0.04	0.04

$\sigma.\sigma$ strengths are quite different for ESC and ND, so further trials and improvements are required.

Sensitive interaction dependence
Nijmegen NHC-D vs. ESC04d

- **Different partial-wave contributions**
  NHC-D (large p-state attraction) vs. ESC04d(s-state)
- **ESC04d (quite large spin- & isospin-dependence)**

Table 1: Ξ single particle energies U_Ξ and conversion widths Γ_Ξ at normal density calculated with ESC04d and NHC-D. S-state contributions in $(TSLJ)$ states and total P-state contributions are also given. All entries are in MeV.

	$^{11}S_0$	$^{13}S_1$	$^{31}S_0$	$^{33}S_1$	P	U_Ξ	Γ_Ξ
ESC04d($\alpha = 0$)	6.4	−19.6	6.4	−5.0	−6.9	−18.7	11.4
ESC04d($\alpha = .18$)	6.3	−18.4	7.2	−1.7	−5.6	−12.1	12.7
NHC-D	−2.6	0.7	−2.3	−0.4	−16.8	−21.4	1.1

Trying to use the most recent Ξ-N interaction from Nijmegen (ESC08)

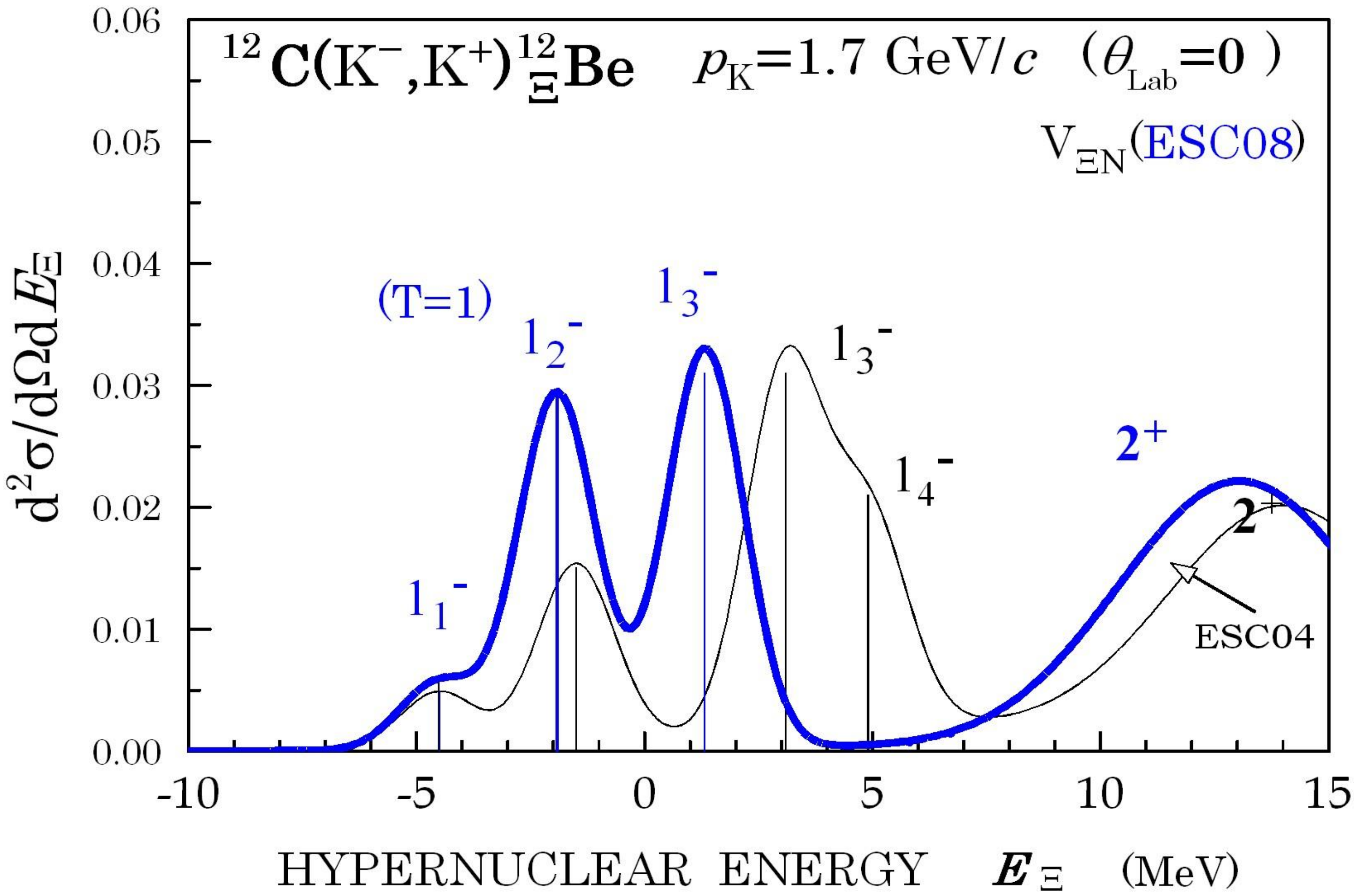
Table 1: Partial wave contributions to $U_\Xi(\rho_0)$

model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ
ESC08	0	4.0	−2.7	0.2	−2.2	0.6	−1.1		
	1	7.0	−19.5	−0.3	0.1	−3.6	−0.7	−18.0	6.0
ESC04d	0	6.4	−19.6	1.1	1.2	−1.3	−2.0		
	1	6.4	−5.0	−1.0	−0.6	−1.4	−2.8	−18.7	11.4

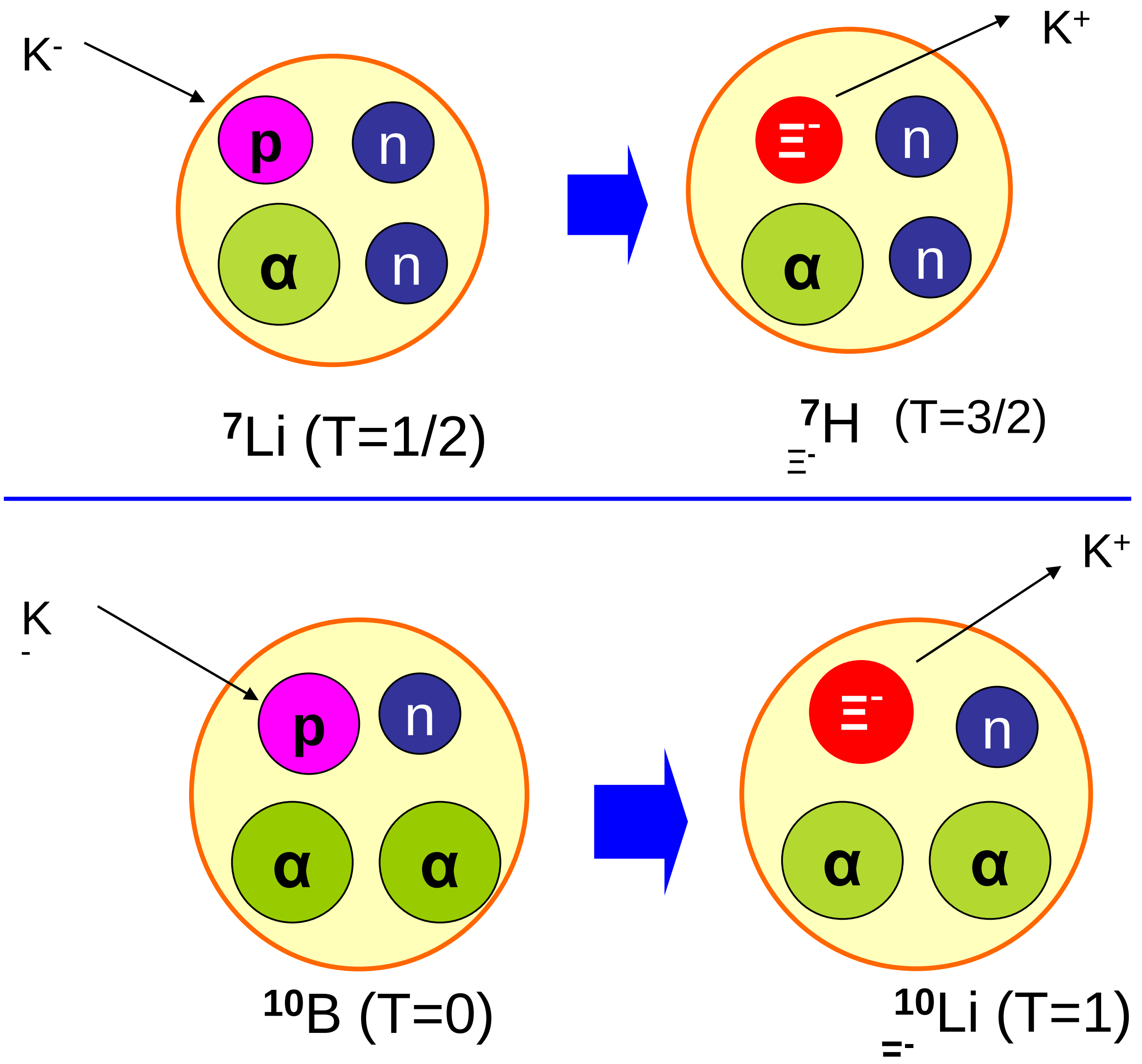
- Let us wait for the J-PARC Day-1 Exp. by Nagae et al, which will provide us a very important restriction on V(Ξ-N).

ESC04 modified to be ESC08 !

(continuum bump should be larger)

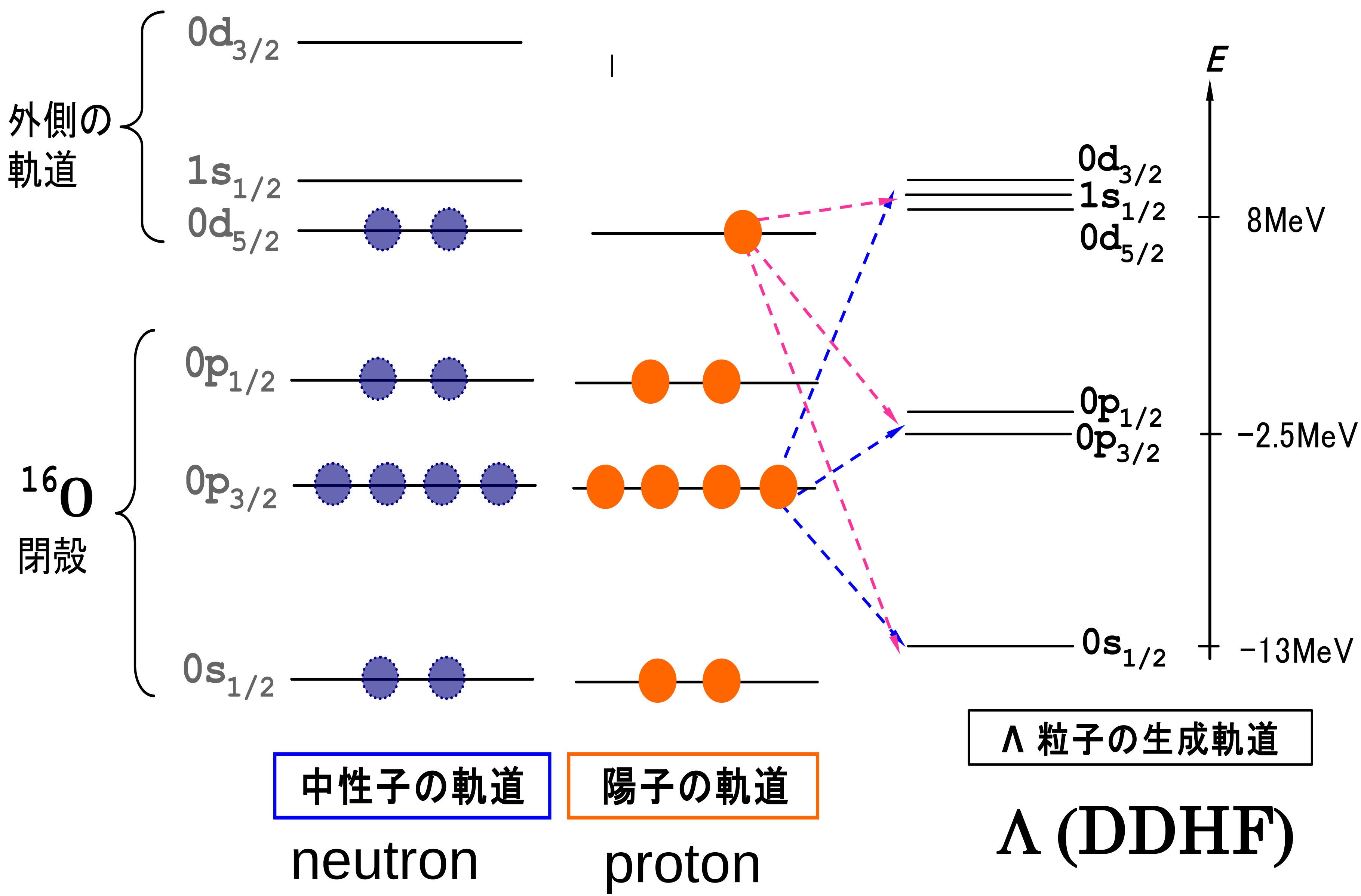


As the second best candidates to extract information about the spin-, isospin-independent term V_0, we propose to perform…

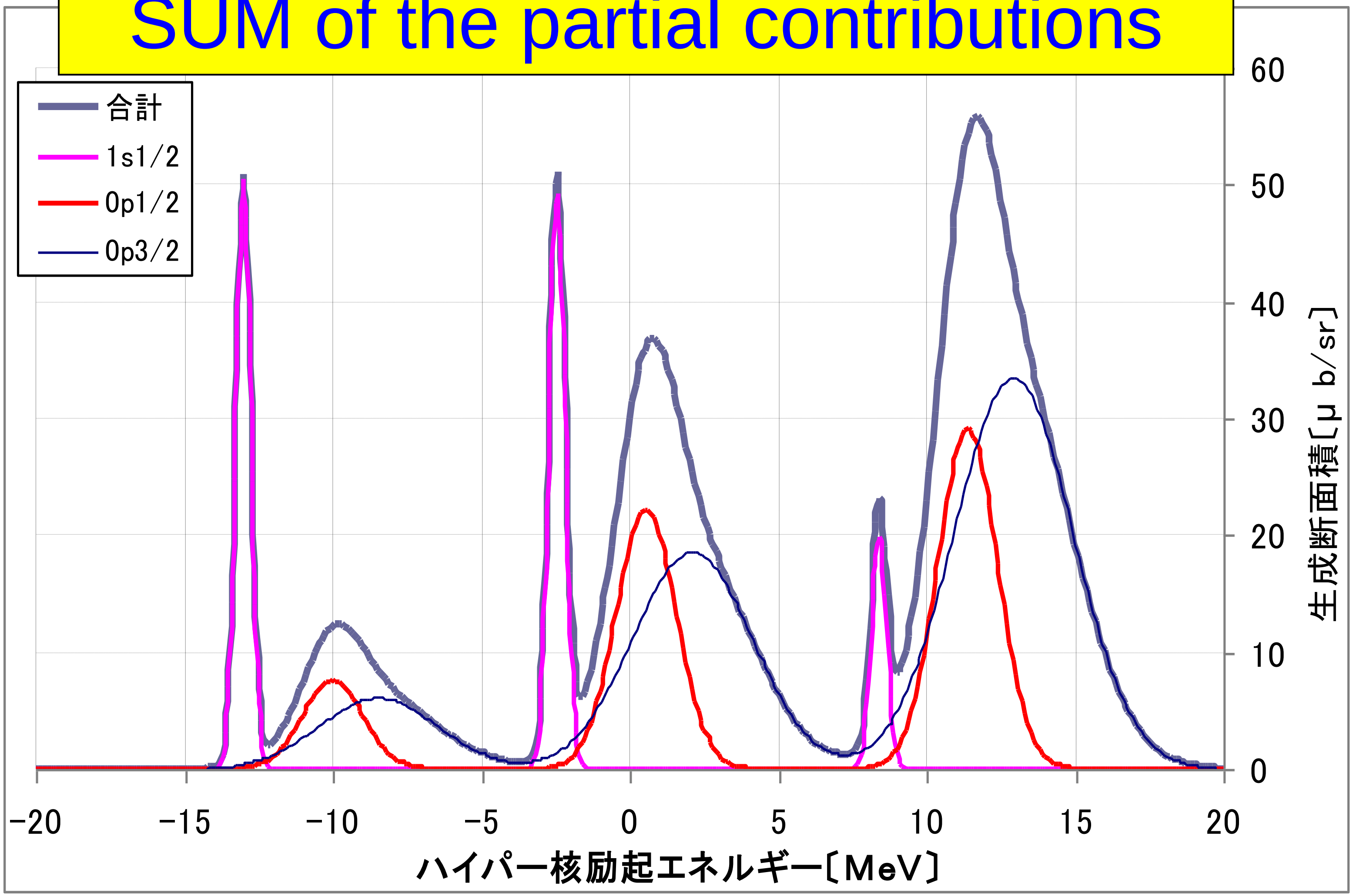


Why they are suited for investigating V_0?

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

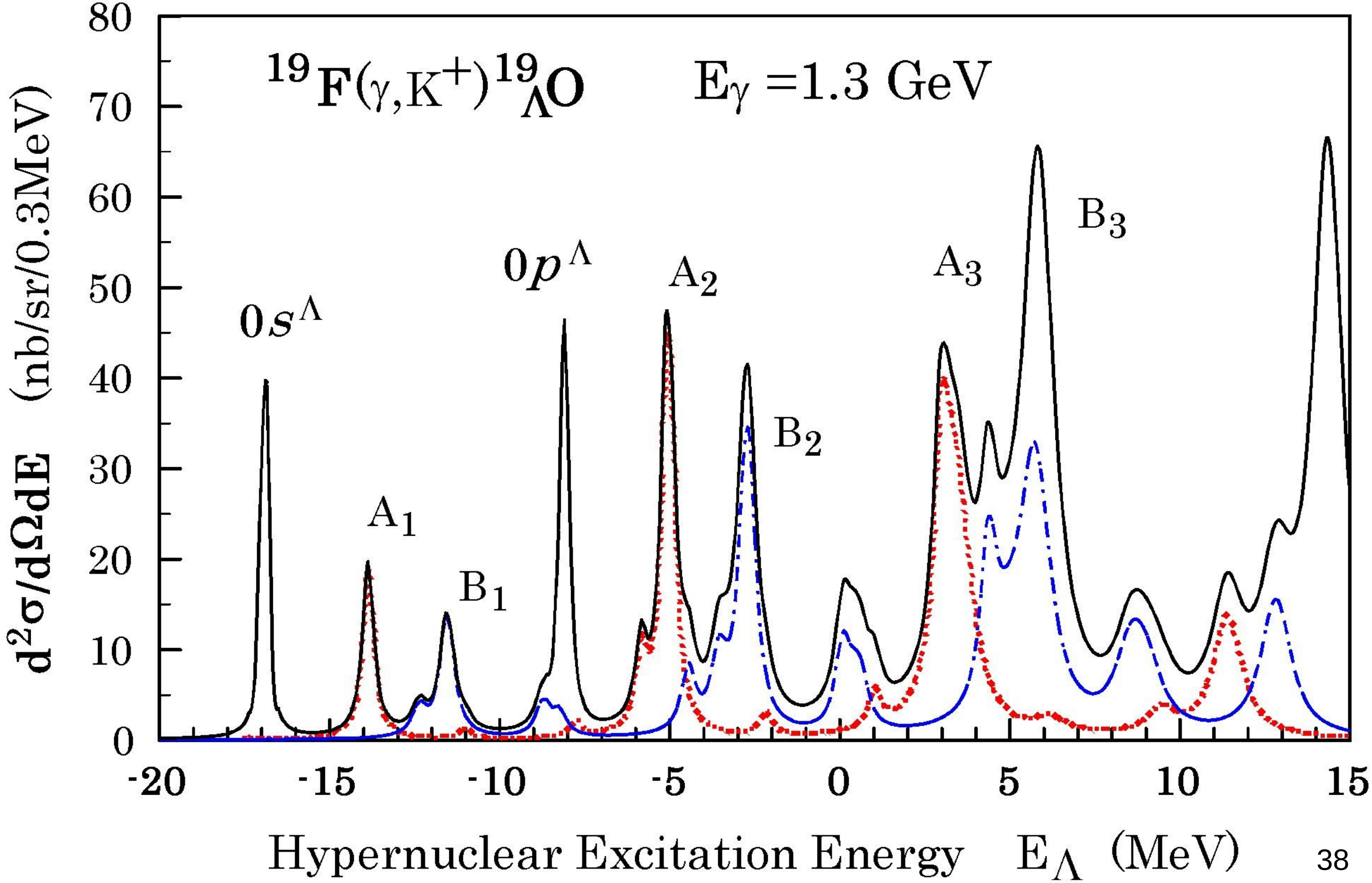


^{19}F(γ,K^{+}) $_{\Lambda}{}^{19}$O
SUM of the partial contributions



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

Lightest sd-shell target: ^{19}F

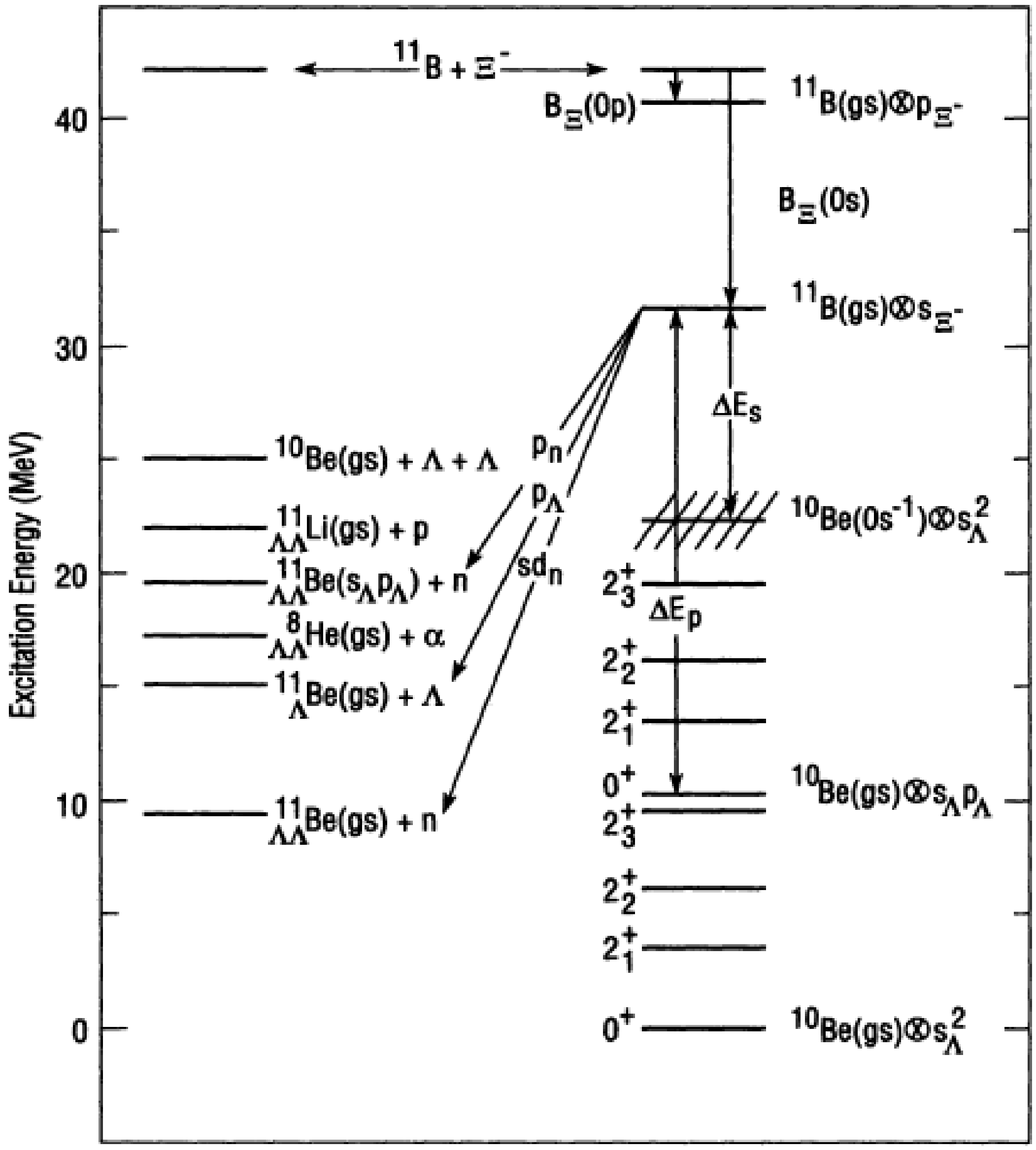


1-Skipped)
discussion

on

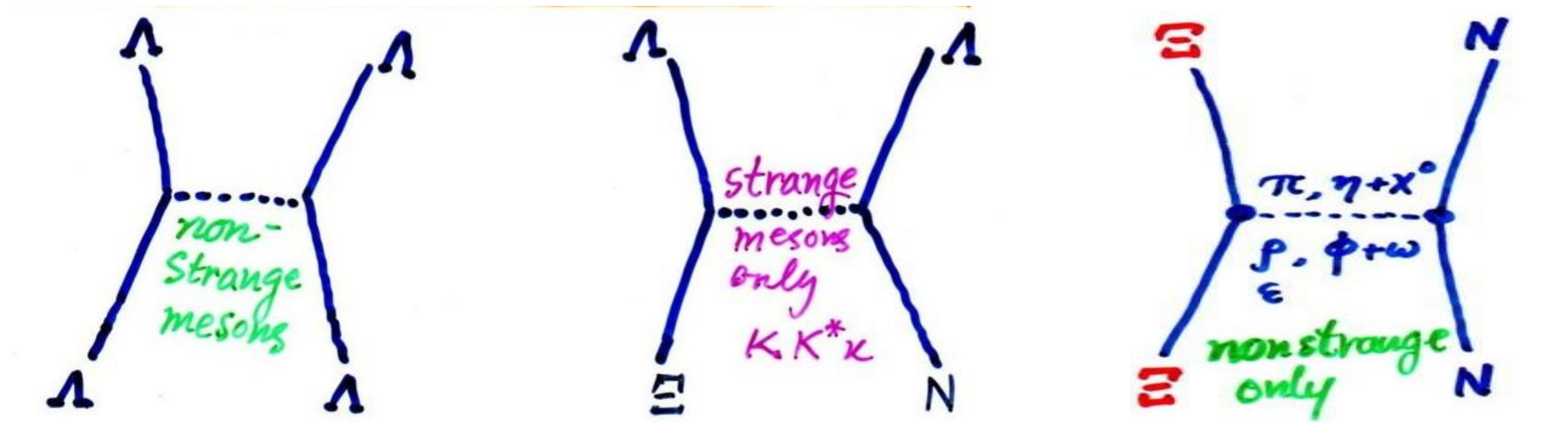
Widths of
Xi states:
Xi-LLmixing

D. J. Millener, C. B. Dover and A. Gal



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 X-hypernucleus via the $^{12}C(K^-,K^+)\,_{\Xi}^{12}Be$ reaction" by T. Nagae et al.

→ Realistic Calculations are required.

Summary (proposal) for Ξ-hypernuclear exp. programs to be done at J-PARC

important point is to extract a firm constraint on the Ξ-N central force

(Meson theory shows strong spin-isospin dependence)

- To realize this purpose, I propose to choose odd-Z natural targets such as

  19F (18O+p), 27Al (26Mg+p),

  31P (30Si+p),……. (Cal. In progress