Multi-configuration calculations of hypernuclear photoproduction spectra to shed light on new capability

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1. Basic motivations

(1) p-shell nuclei and hypernuclei provide a variety of interesting phenomena (shell-, cluster-, and coexistent characters), depending on E_x and mass.

(2) **Progress of high-precision experiments** in hypernuclear spectroscopy (γ-ray , (e,e’K+))

(3) Detailed look in Jlab (e,e’K+) spectroscopic data requires **an extended description with multi-configuration parity-mixing mediated by hyperon**

(4) Focusing on **multi-configuration shell-model applications** to ^{10}**B**(γ,K+)$^{10}{}_{\Lambda}$**Be** and ^{12}**C**(γ,K+)$^{12}{}_{\Lambda}$**B.**

2. High-precision hypernuclear reaction spectroscopy, esp., in (e,e'K$^+$) at JLab.

2(a). γ-ray spectroscopy

γ-ray measurements:
amazing E resolution
ΔE ≈ several keV

p-shell (right fig.)
sd-shell ($^{19}{}_{\Lambda}$F)
s-shell ($^{4}{}_{\Lambda}$He)

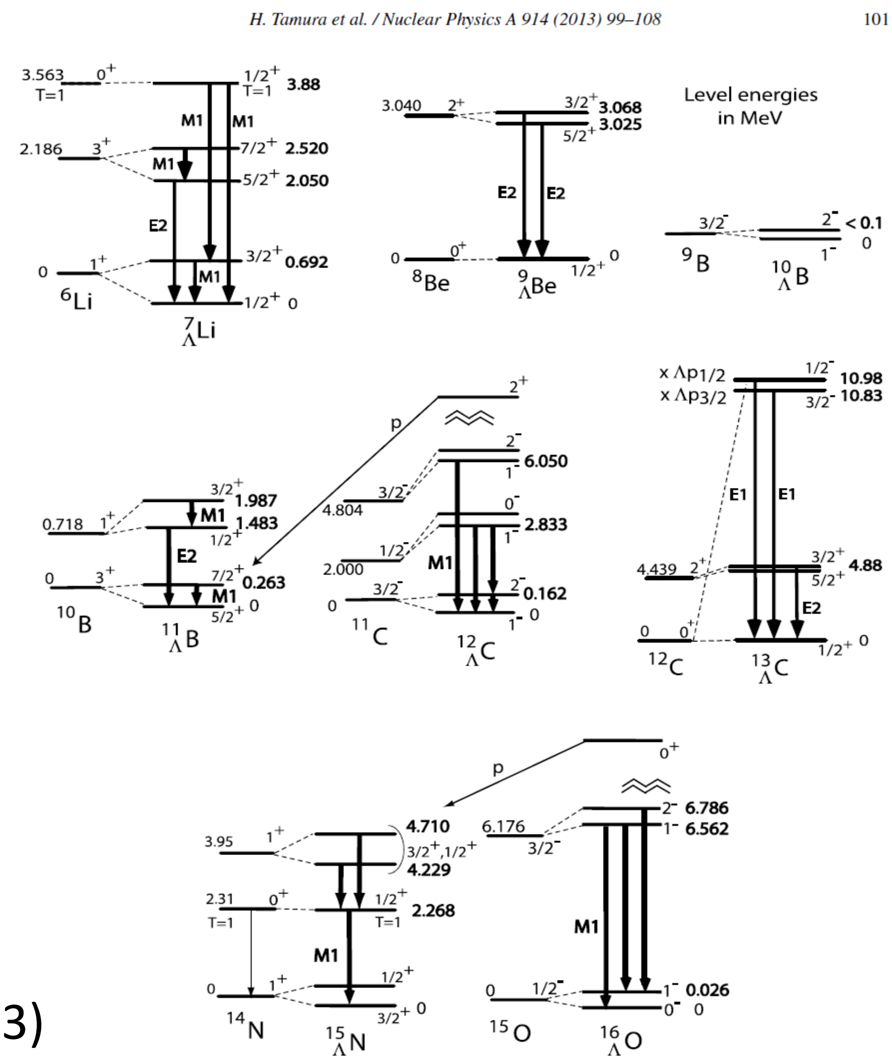


Figure taken from H. Tamura et al., Nucl. Phys. A 914 (2013)

γ-ray spectroscopy (s- & sd-shell)

γ-ray measurements:
amazing E resolution
ΔE ≈ several keV

s-shell ($^{4}_{\Lambda}$He)

sd-shell ($^{19}_{\Lambda}$F)

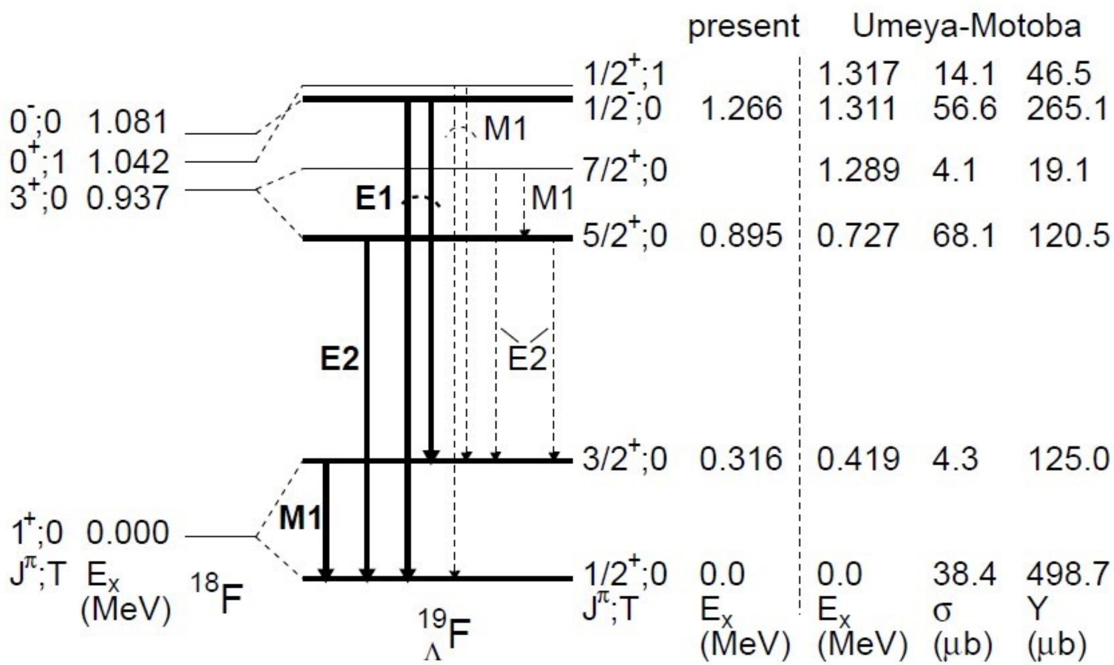


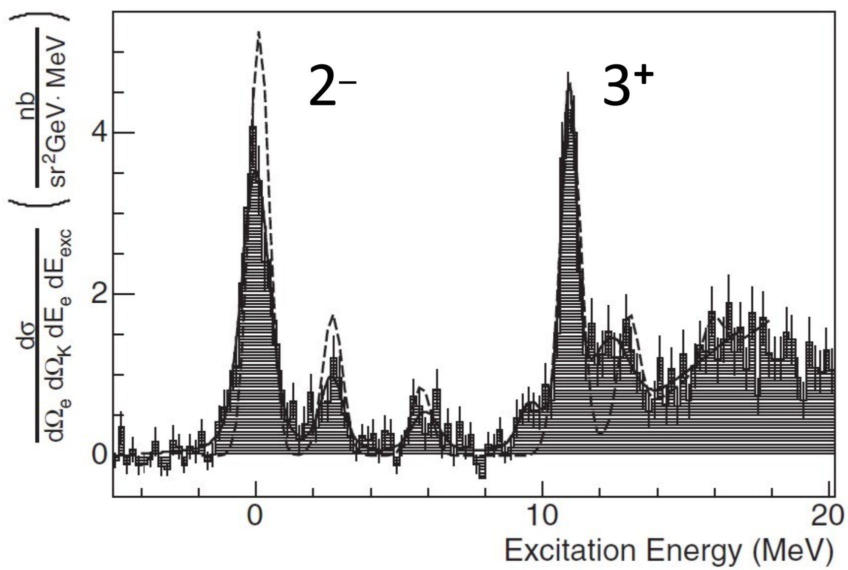
Figure taken from S.B. Yang, et al., , Phys. Rev. Lett. 120, (2018).
Theory: Umeya and Motoba, Nucl. Phys. A954, 242(2016),
(taking account of both positive and negative parity core states)

2(b). (e,e'K+) reaction spectroscopy

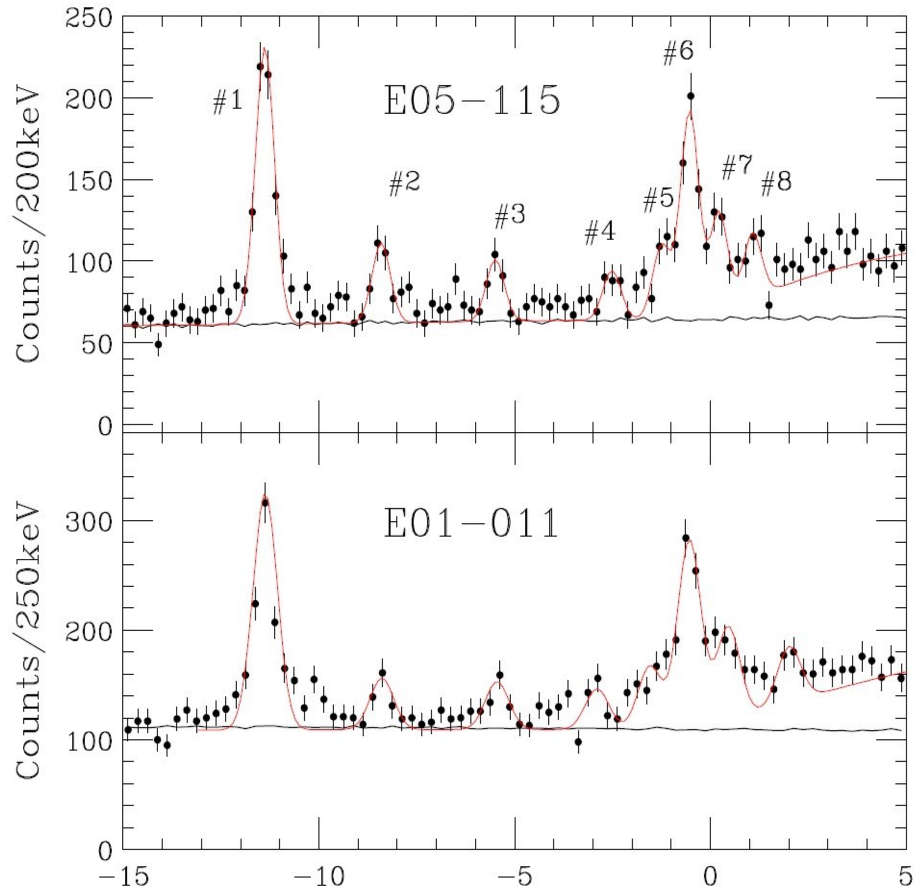
Success of *high-resolution* experiments at JLab

^{12}**C**(e,e'K$^+$) $^{12}{}_{\Lambda}$**B**

Hall A: M. Iodice et al., PRL 99 (2007) **ΔE=0.67** MeV



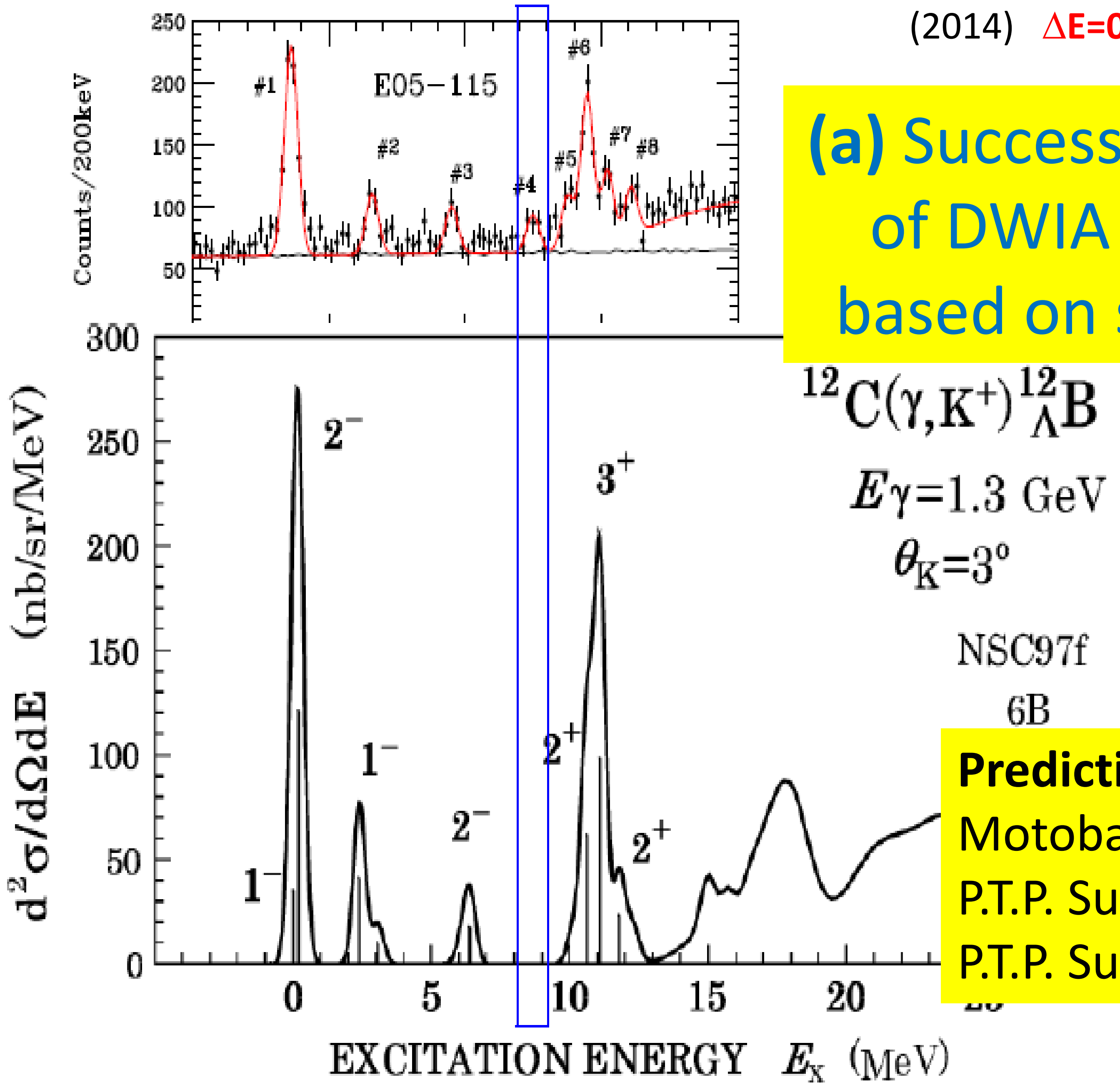
Hall C: L. Tang et al., PRC 90 (2014) **ΔE=0.54** MeV



$[p^{-1}p^{\Lambda}]\Delta L=2, \Delta S=1; \Delta J=3$

Hall C: L. Tang et al., PRC 90 (2014) **ΔE=0.54** MeV

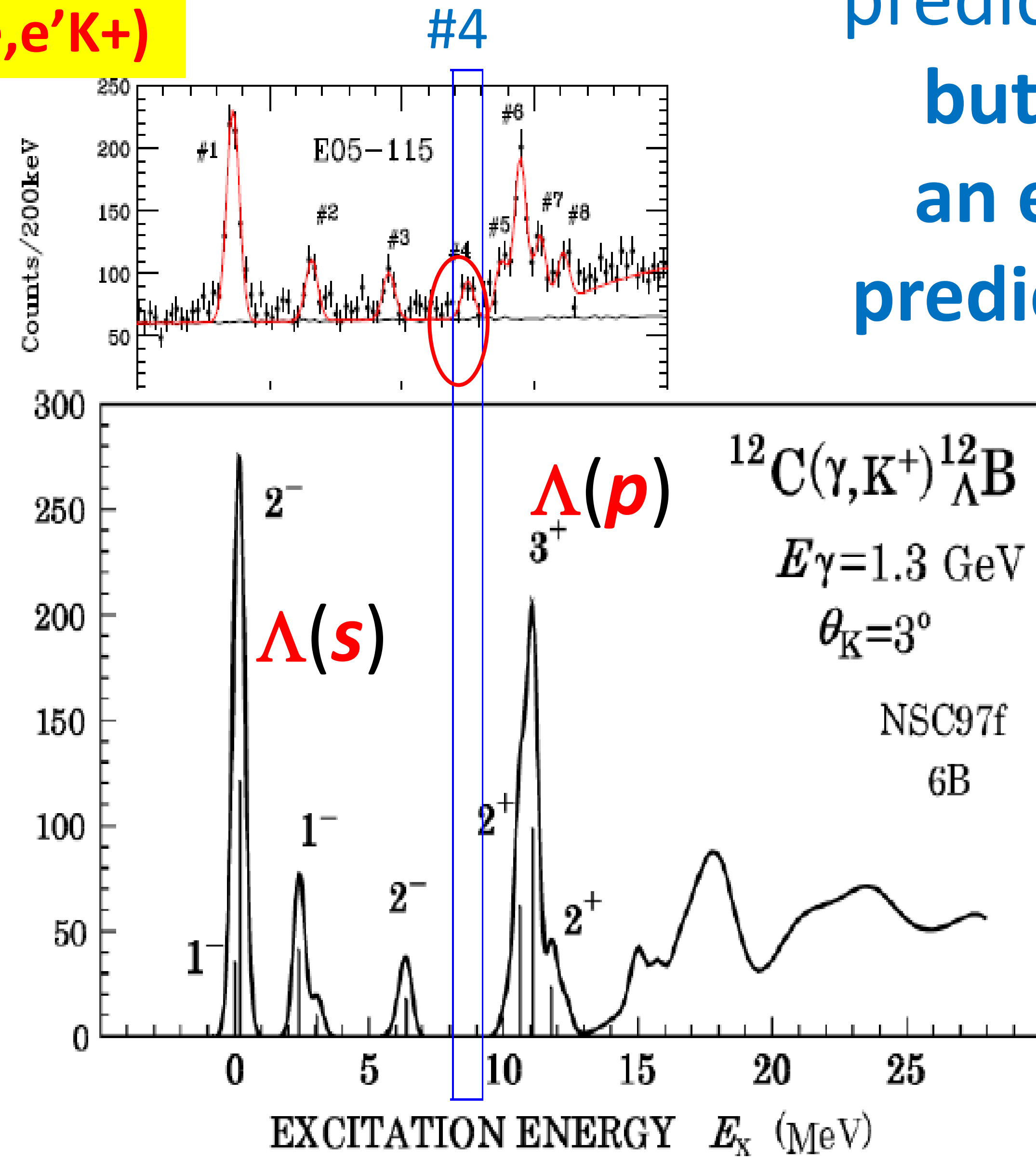
(a) Successful prediction of DWIA Calculation based on standard WF



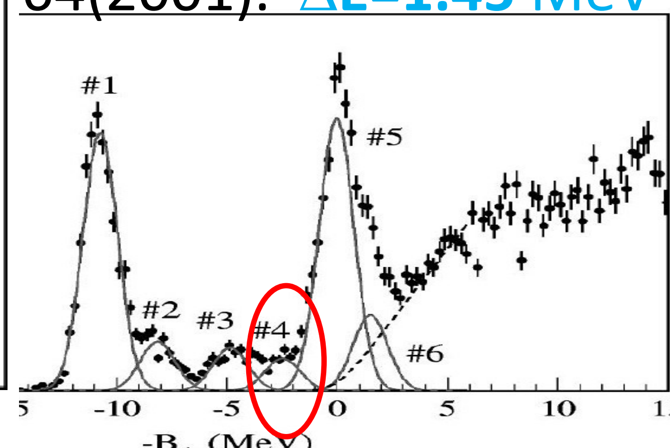
Predictions: DWIA CAL.
Motoba, Sotona, Itonaga,
P.T.P. Suppl.117 (1994);
P.T.P. Suppl.185 (2010)

These JLab experiments confirmed the theoretical predictions on one hand, **but**, at the same time, **an extra peak (#4) not predicted so far attracts a new theoretical challenge.**

(e,e'K+)



H. Hotchi et al., P.R.C 64(2001). **ΔE=1.45** MeV



$(\pi+,K+)^{12}{}_{\Lambda}C$

Exp XS and DWIA estimates are in good agreement. The framework of treating the reaction is proved to be powerful.

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

DWIA + SLA amplitudes

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

E01-011

~~E05-115~~ Experiment [9] $\theta_{\gamma K} \approx 6.8^\circ$				CAL: SLA [16] at $\theta_K = 7^\circ$				CAL: S6B [17]	
Peak	$-B_\Lambda$(MeV)	E_x (MeV)	$d\sigma/d\Omega$	J_f	E_x (MeV)	$d\sigma/d\Omega$	Sum	$d\sigma/d\Omega$	Sum
# 1-1	−11.524	$(0.0)_{GS}$		1^-_1	$(0.0)_{GS}$	21.1		10.5	
# 1-2	−11.345	(0.179)	101.0	2^-_1	(0.186)	89.3	100.4	63.1	73.6
# 2	−8.415	(3.109)	33.5	1^-_2	(2.398)	48.4	56.1	19.0	24.1
				0^-_1	(3.062)	7.7		5.2	
				2^-_2	(5.022)	7.0		4.9	
# 3	−5.475	(6.049)	26.0	2^-_3	(6.267)	11.8	23.8	8.4	15.5
				1^-_3	(6.389)	5.0		2.3	
# 4	−2.882	(8.857)	20.5						
				2^+_1	(11.000)	1.3		1.4	
# 5	−1.289	(10.235)	31.5	1^+_1	(11.120)	8.2	9.5	5.1	6.5
# 6	−0.532	(10.992)	87.7	3^+_1	(11.081)	77.6	130.7	57.1	81.1
				2^+_2	(11.610)	53.2		24.0	
				1^+_2	(12.129)	6.1		7.1	
# 8	0.973	(12.497)	28.5	2^+_3	(12.784)	20.0	29.8	9.1	20.4
				1^+_3	(13.176)	3.7		4.2	

3. An extended treatment of multi-config. wave functions---just to explain a new concept

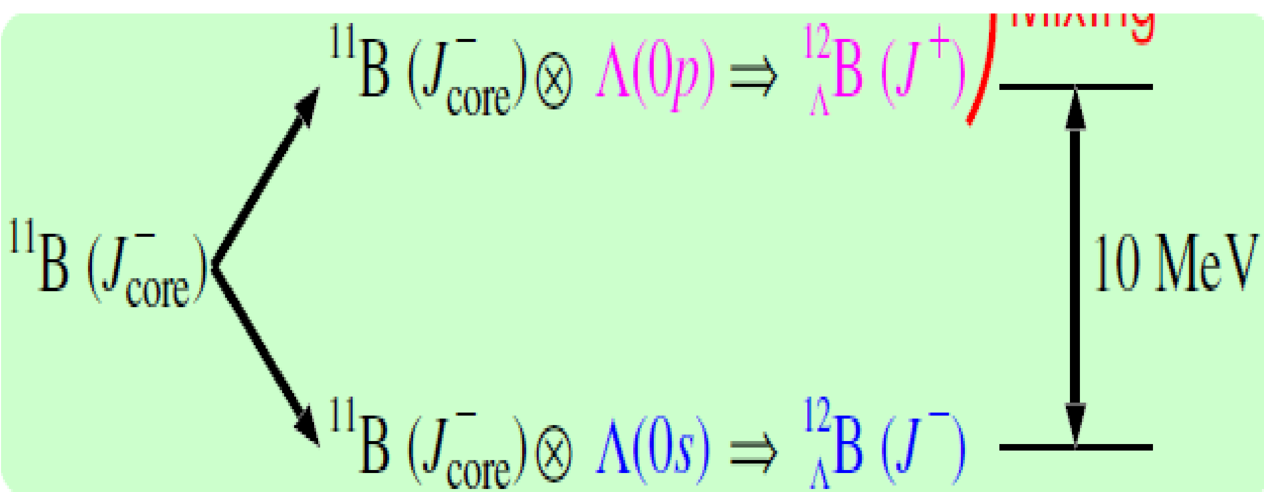
Standard configuration assumed so far: (in case of $^{12}{}_{\Lambda}$B)

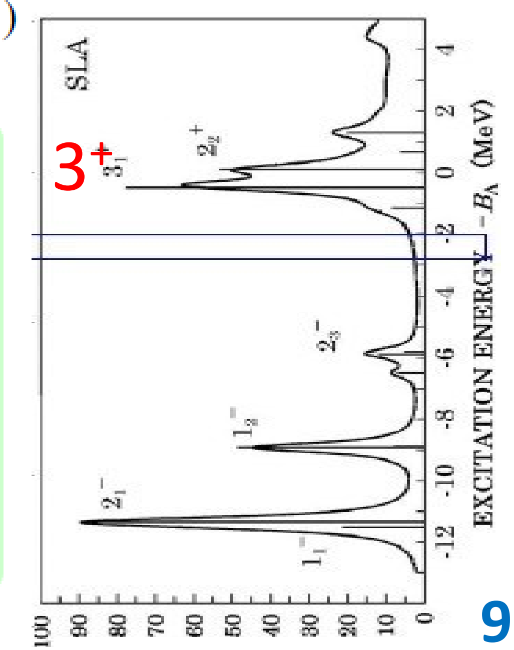
Model space for ^{11}B core

(a) **ordinary model space** J^{-}_{core} $(0s)^4\,(0p)^7$ $(0p\text{-}0h)$

Ordinary model space for $^{12}_{\Lambda}$B hypernuclei

(a) $J^{-}_{\text{core}} \otimes 0s^{\Lambda} \Rightarrow {}^{12}_{\Lambda}\text{B}(J^{-})$ (b) $J^{-}_{\text{core}} \otimes 0p^{\Lambda} \Rightarrow {}^{12}_{\Lambda}\text{B}(J^{+})$





Two kinds of extensions to include both natural and unnatural parity core states

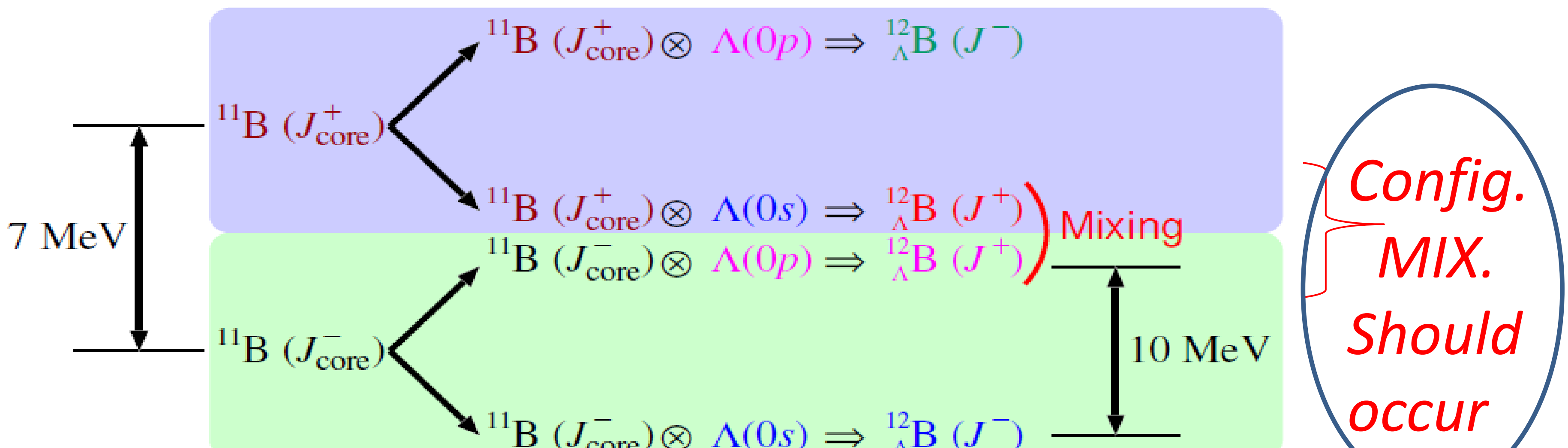
Extention (1) **1p-1h core excitation is taken into account**

(c) $J^{+}_{\rm core} \otimes 0s^{\Lambda} \Rightarrow {}^{12}_{\Lambda}{\rm B}(J^{+})$ (d) $J^{+}_{\rm core} \otimes 0p^{\Lambda} \Rightarrow {}^{12}_{\Lambda}{\rm B}(J^{-})$

Extention (2) **Configurations mixed by ΛN interaction**

(a) $J^{-}_{\rm core} \otimes 0s^{\Lambda} \oplus J^{+}_{\rm core} \otimes 0p^{\Lambda} \Rightarrow {}^{12}_{\Lambda}{\rm B}(J^{-})$

(b) $J^{-}_{\rm core} \otimes 0p^{\Lambda} \oplus J^{+}_{\rm core} \otimes 0s^{\Lambda} \Rightarrow {}^{12}_{\Lambda}{\rm B}(J^{+})$



$$\varepsilon(0p^{\Lambda}) - \varepsilon(0s^{\Lambda}) \approx E({}^{11}{\rm B}(J^{+}_{\rm core})) - E({}^{11}{\rm B}(J^{-}_{\rm core}))$$

$\longrightarrow$ Strong mixing between $\left[{}^{11}{\rm B}(J^{-}_{\rm core}) \otimes \Lambda(0p)\right]$ and $\left[{}^{11}{\rm B}(J^{+}_{\rm core}) \otimes \Lambda(0s)\right]$

Our new theoretical challenge:

Both extensions (1)+(2) are taken into account simultaneously to describe **$^{12}{}_{\Lambda}$B**

"parity-mixing mediated by Λ"

(a new concept seen only in hypernucleus)

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

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

→ Energy levels, Proton-pickup S factors,

→→ DWIA cross section of **^{12}C** (e,e'K+) **$^{12}{}_{\Lambda}$B**

New transition components connected via (γ,K$^+$) in extended model space

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

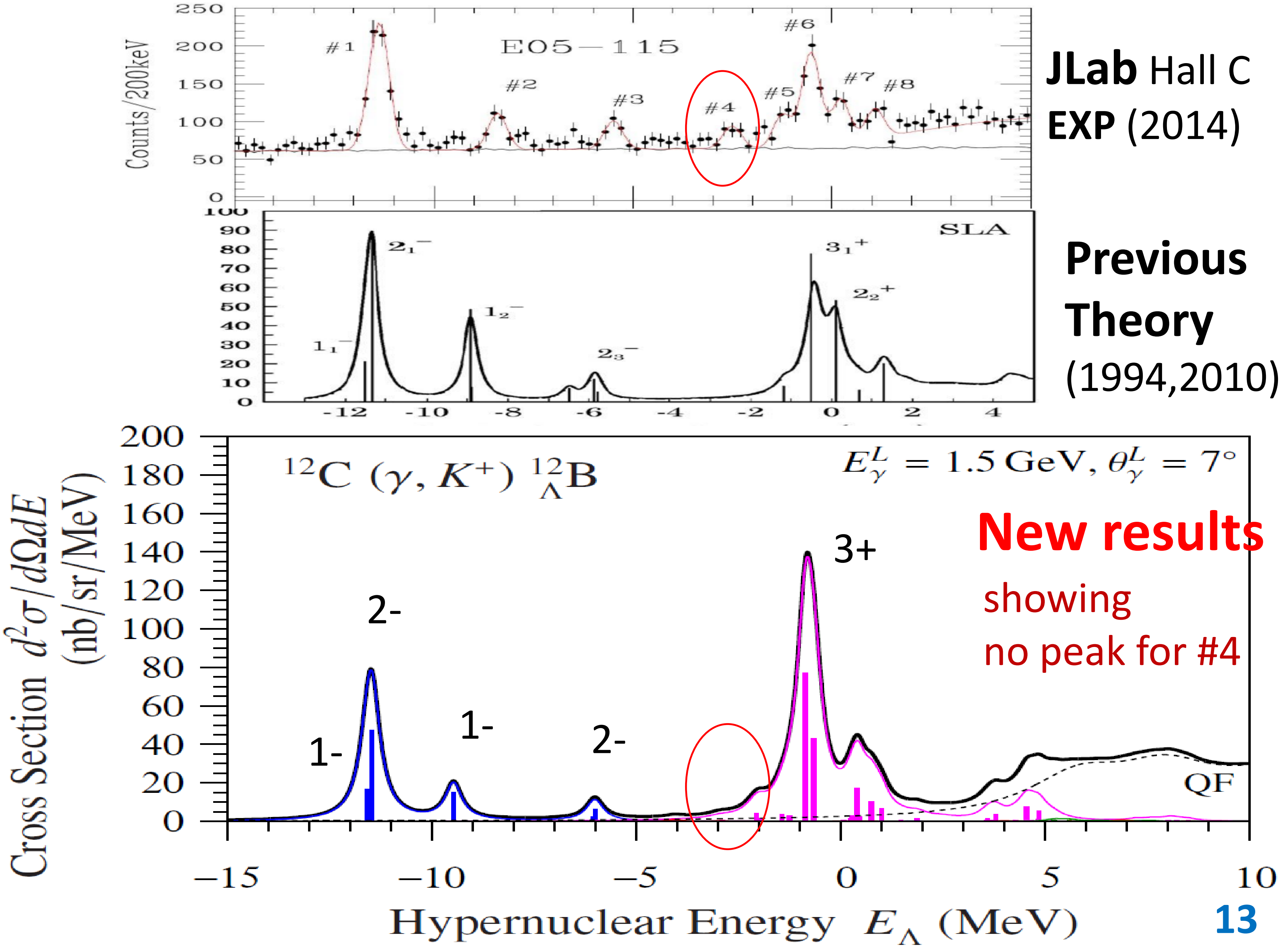
(In the past cals, **only green arrows** are taken into account.)

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

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

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

Problems to be checked: What kind of effective interactions should be used in describing the WF in the extended model.



E05−115
#1
#2
#3
#4
#5
#6
#7
#8
Counts/200keV
JLab Hall C
EXP (2014)
SLA
2_1^-
1_1^-
1_2^-
2_3^-
3_1^+
2_2^+
Previous
Theory
(1994,2010)
$^{12}C\ (\gamma, K^+)\ ^{12}_{\Lambda}B$
$E^L_\gamma = 1.5\,\mathrm{GeV},\ \theta^L_\gamma = 7°$
Cross Section $d^2\sigma/d\Omega dE$ (nb/sr/MeV)
2-
1-
1-
2-
3+
QF
New results
showing
no peak for #4
Hypernuclear Energy E_Λ (MeV)

< This is not the end of story, but the beginning. >

Before discussing the ***reason for no peak result on #4 peak*** observed in $^{12}{}_{\Lambda}$**B**, let us look next at the theoretical result for $^{10}\mathrm{B}(\gamma,K^{+})^{10}{}_{\Lambda}\mathrm{Be}$.

At the same time, we perform calculations for the recoilless $^{9}\mathrm{Be}(K^{-},\pi^{-})\,^{9}{}_{\Lambda}\mathrm{Be}$ and $^{10}\mathrm{B}(K^{-},\pi^{-})^{10}{}_{\Lambda}\mathrm{B}$ reactions in order to get insight for the different situation.

4. Parity-mixed multi-configuration treatment for $^{10}B(\gamma,K^+)^{10}{}_{\Lambda}Be$

The wave function consists of two kinds of configurations: core-parity mixed by Λ

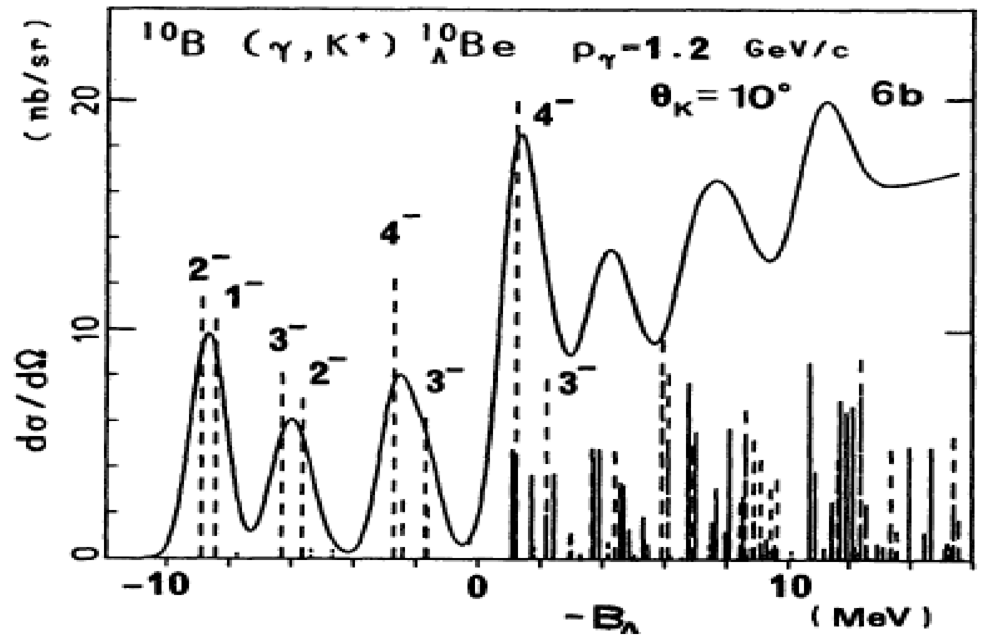
$$^{10}_{\Lambda}Be(J_H^-) = \Sigma[\,^9Be(J_c^-) \times s_\Lambda]^{(0)} + \Sigma\,[\,^9Be(J_c^+) \times p_\Lambda]^{(2)}$$
$$^{10}_{\Lambda}Be(J_H^+) = \Sigma\,[\,^9Be(J_c^-) \times p_\Lambda]^{(1)} + \Sigma[\,^9Be(J_c^+) \times s_\Lambda]^{(1)}$$

The target g.s. wave function is described correspondingly

$$^{10}B(J_g^+) = \Sigma[\,^9Be(J_c^-)\ \times\ j_p^N] + \Sigma\,[\,^9Be(J_c^+)\ \times\ j_{s,sd}^N]$$

For nuclear parts one may adopt other sophisticated shell models , cluster models, AMDs, etc.

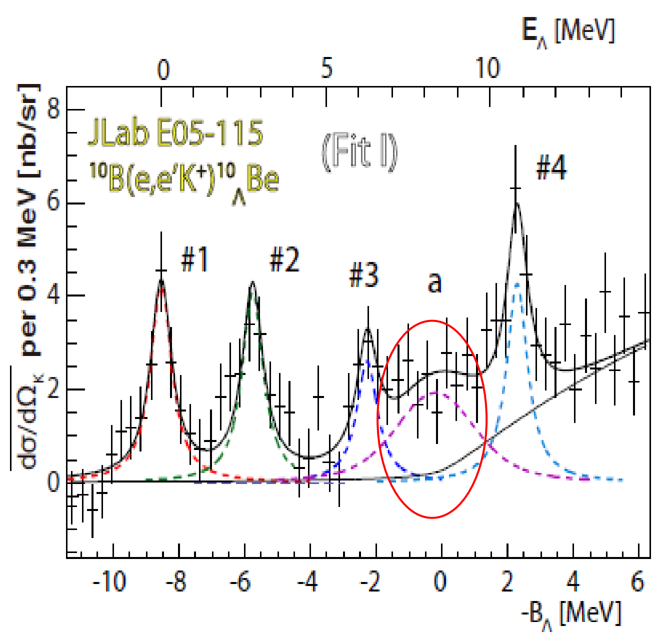
The first (γ,K⁺) prediction made so far within the standard model



Shell model: T. Motoba, M. Sotona, K. Itonaga, P.T.P. Suppl. **117**, 123 (1994).

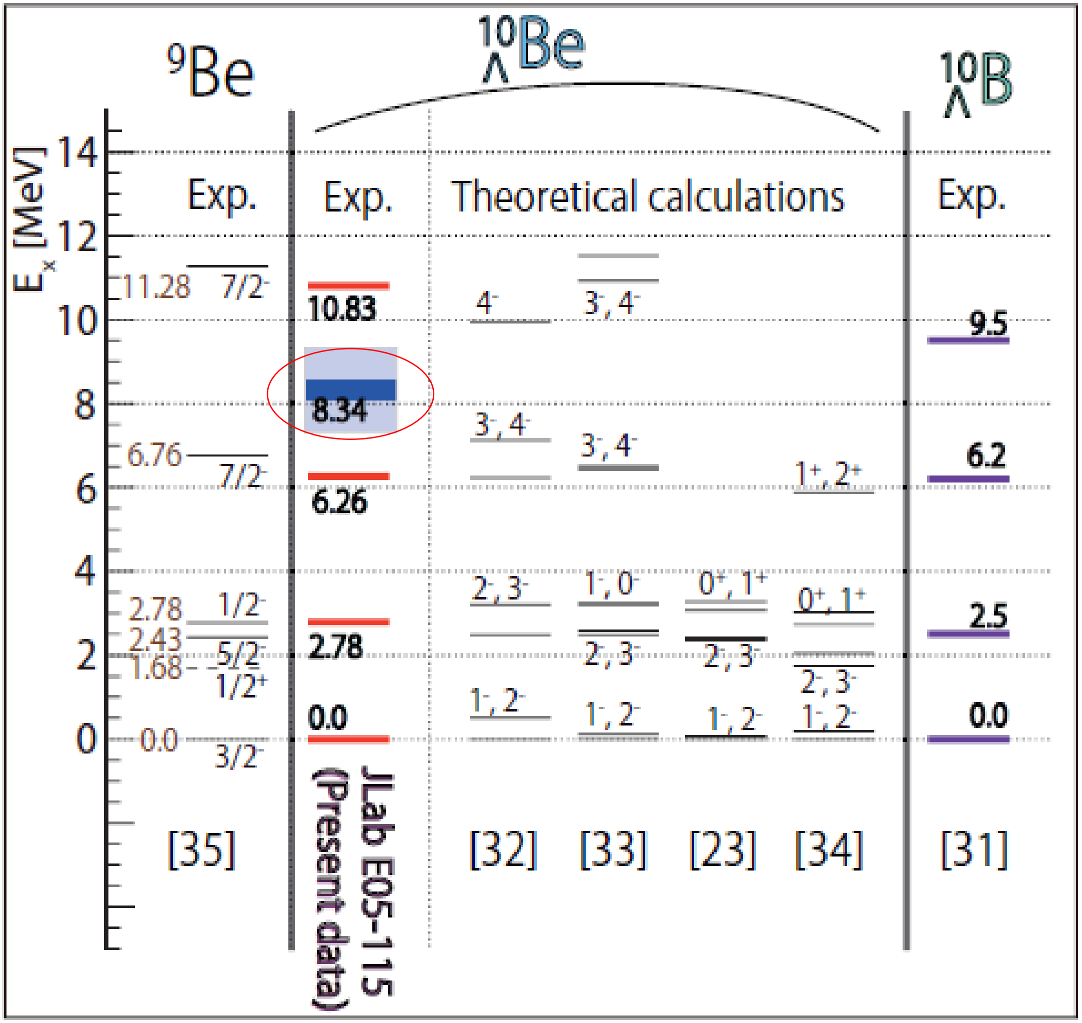
The first data came recently

T. Gogami et al., P.R. C **93** (2016)



Major predicted peaks are clearly confirmed, **but....** again we have extra yields (# **a**) that are not explained in the previous theory.

Theoretical energy levels (w/o parity-mixing)



[32] **Shell model:**
T. Motoba, M. Sotona, K. Itonaga, P.T.P. Suppl. **117**, 123 (1994).
T. Motoba, P. Bydzovsky, M. Sotona, K. Itonaga, P.T.P. Suppl.**185** (2010).

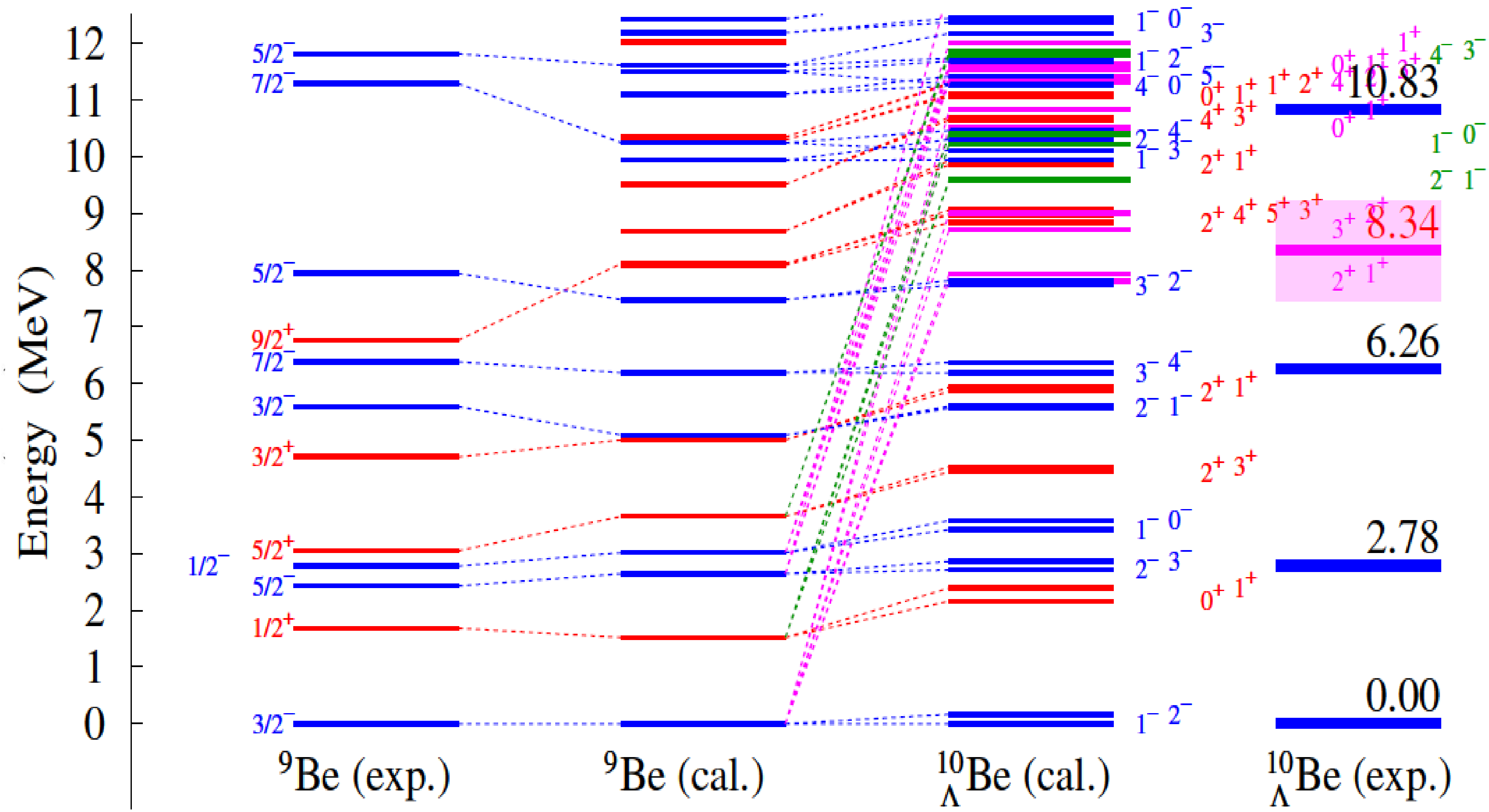
[33] **Shell model:**
D.J. Millener, N.P.A **881**, 298 (2012).

[23] **Cluster model:**
E. Hiyama, Y. Yamamoto, P.T.P. **128**, 105 (2012).

[34] **AMD model:**
M. Isaka et al., Few-Body Syst. **54**, 1219 (2013)

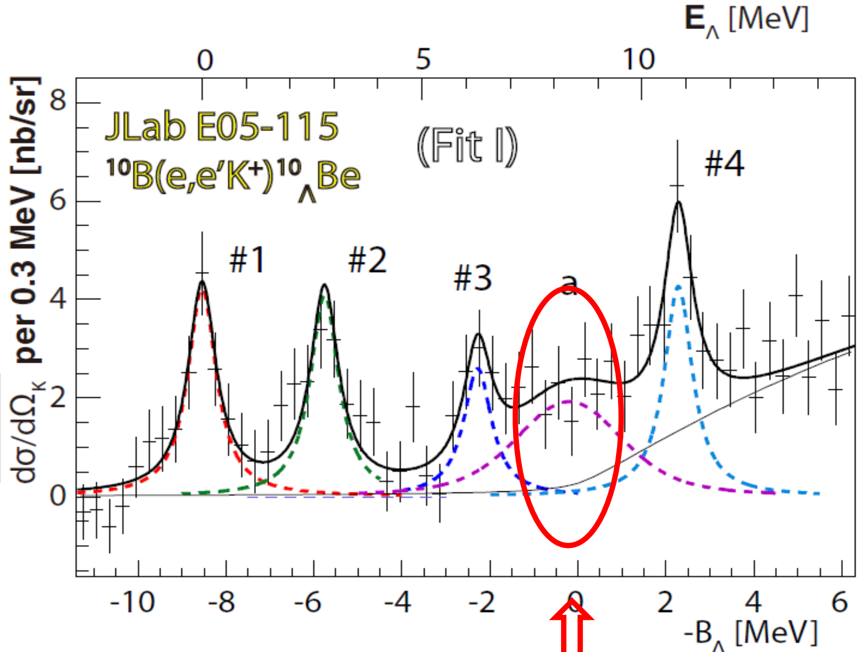
JLab exp. T. Gogami et al., P.R. C **93**, 034314 (2016)

Energy levels obtained in the parity-mixed multi-configuration calculations (α-breaking included)

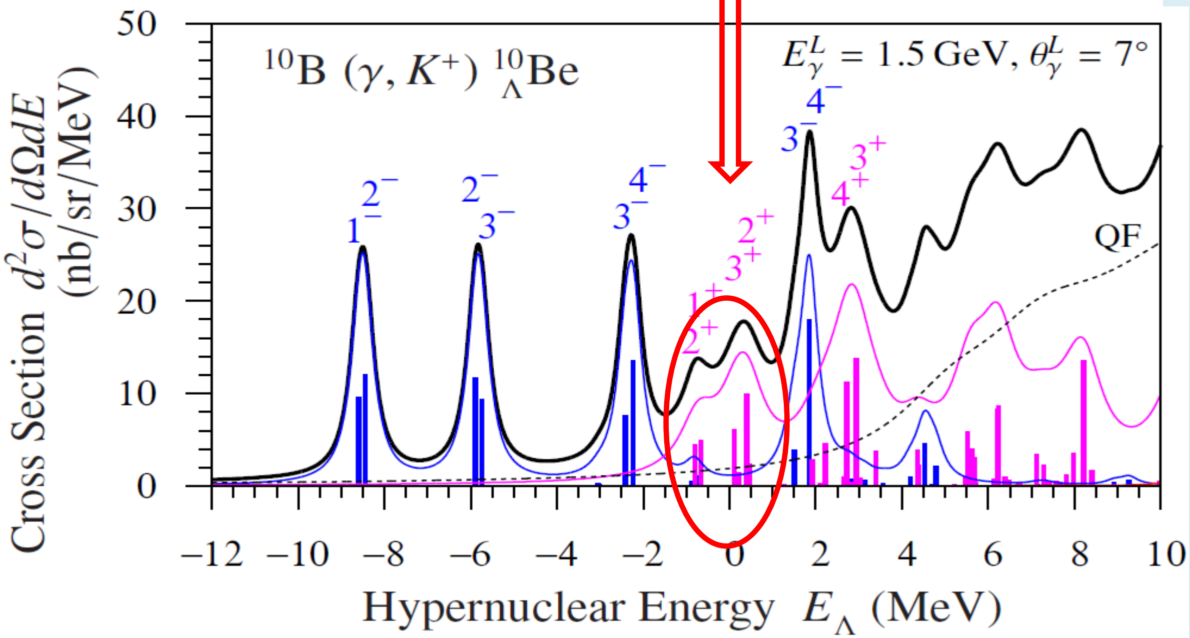


NEW *NEW*

^{9}Be core nuclear energy levels are satisfactory.



Jlab: ^{10}**B**(e,e'K+)$^{10}{}_{\Lambda}$**Be**
Exp. T. Gogami et al.,
P.R. C **93** (2016)



New theoretical result
of ^{10}**B**(γ,K+)$^{10}{}_{\Lambda}$**Be**
obtained with the parity-mixed multi-configuration wave functions.

The new model can explain remarkably the extra bump #a.

Comparison of energies and cross sections for 5 peaks

E_γ = 1.5 GeV
θ = 7 deg

EXP = T. Gogami et al, PRC93 (2016)

^{9}Be (J_i)			$_\Lambda^{10}$Be (J_k) CAL					EXP			Fit I
J_i	E_i (exp) C2S	E_i (cal) C2S	J_k	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]		exp peak	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]
$3/2^-$	0.000	0.000	1^-	0.000	−8.600	9.609	**21.62**	#1	0.00	−8.55±0.07	**17.0±0.5**
	1.0(rel)	*1.0(rel)*	2^-	0.165	−8.435	12.008					
$5/2^-$	2.429	2.644	2^-	2.712	−5.888	11.654	**21.05**	#2	2.78±0.11	−5.76±0.09	**16.5±0.5**
	0.958	*1.020*	3^-	2.860	−5.740	9.391					
$7/2^-$	6.380	6.189	3^-	6.183	−2.417	7.625	**21.13**	#3	6.26±0.16	−2.28±0.14	**10.5±0.3**
	0.668	*0.942*	4^-	6.370	−2.230	13.505					
			$2^+(3)$	7.807	−0.793	4.495	**9.46**	#a	8.34±0.41	−0.20±0.40	**23.2±0.7**
			$1^+(3)$	7.935	−0.665	4.968					
			$3^+(2)$	8.712	0.112	6.150	**19.91 (29.37)**				
			$2^+(4)$	8.828	0.228	1.431					
			$2^+(5)$	9.002	0.402	9.893					
			$3^+(3)$	9.059	0.459	2.434					
$7/2^-$	11.283	10.241	3^-	10.105	1.505	3.913	**21.90**	#4	10.83±0.10	2.28±0.07	**17.2±0.5**
	1.299	*1.355*	4^-	10.455	1.855	17.985					
			$1^+(5)$	10.828	2.228	4.598	**29.54 (51.44)**				
			$4^+(3)$	11.318	2.718	11.185					
			$3^+(5)$	11.543	2.943	13.759					

Consisting of several states

Broad peak #a

Agreement is satisfactory (slight overestimates with SLA)

Parity-mixed w.f. of states in the "extra" #a

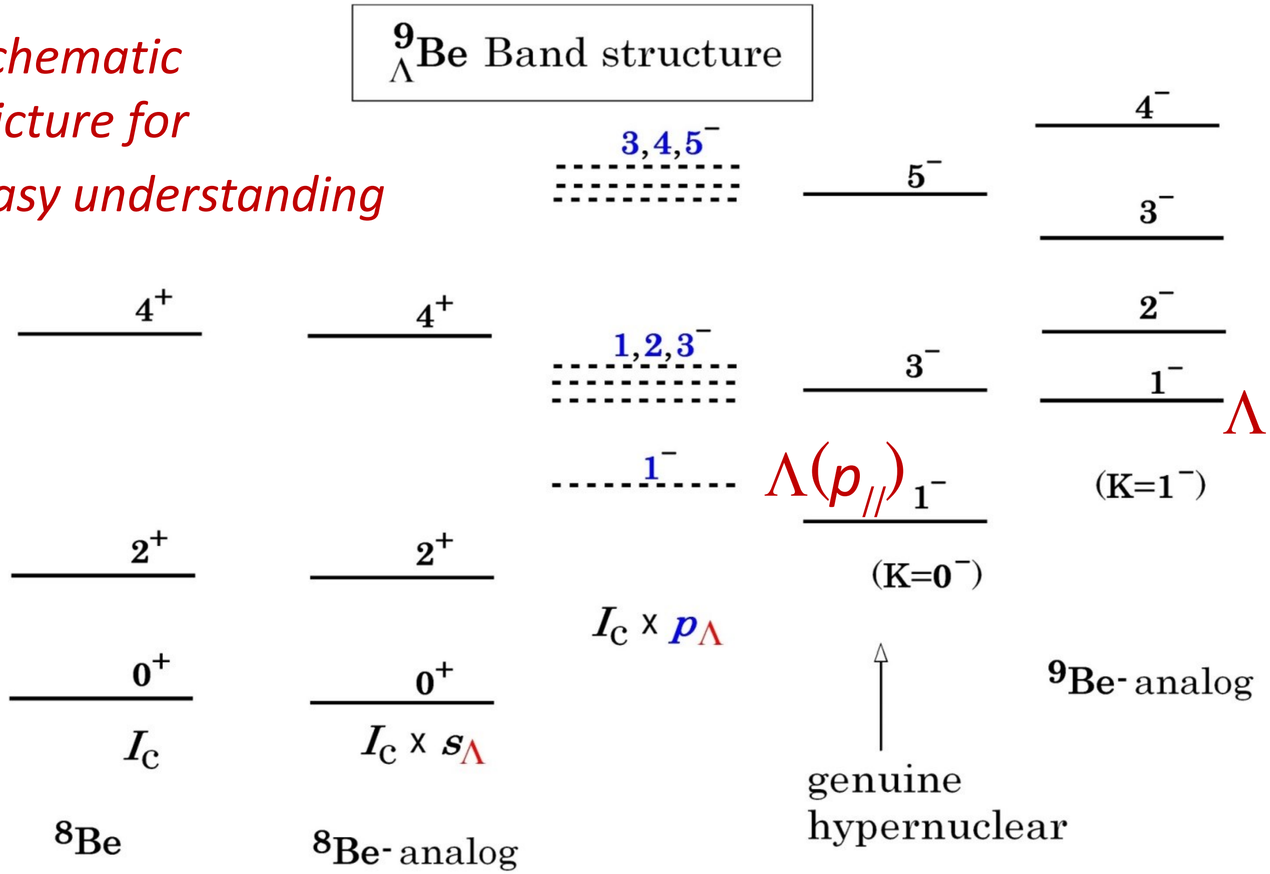
$J^{\pi}_{n}(-B_{\Lambda}[\mathrm{MeV}])$ XS [nb/sr]	$[J^{\pi}_{\mathrm{core}}]j^{\Lambda}$	$[J^{\pi}_{\mathrm{core}}]j^{\Lambda}$	$[J^{\pi}_{\mathrm{core}}]j^{\Lambda}$
$2^{+}_{3}(-0.739)$ 4.49		$[3/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 82.5%	$[5/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 15.8%
$1^{+}_{3}(-0.665)$ 4.97		$[3/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 79.5%	$[5/2^{-}_{1}]p^{\Lambda}_{3/2}$ 17.9%
$2^{+}_{4}(0.228)$ 1.43	$[5/2^{+}_{2}]s^{\Lambda}_{1/2}$ 87.5%	$[3/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 9.4%	$[5/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 2.4%
$2^{+}_{5}(0.402)$ 9.89	$[5/2^{+}_{2}]s^{\Lambda}_{1/2}$ 11.3%	$[3/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 70.9%	$[5/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 10.8%
$3^{+}_{2}(0.112)$ 6.15	$[5/2^{+}_{2}]s^{\Lambda}_{1/2}$ 31.6%	$[3/2^{-}_{1}]p^{\Lambda}_{3/2}$ 55.4%	$[5/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 9.7%
$3^{+}_{3}(0.459)$ 2.43	$[5/2^{+}_{2}]s^{\Lambda}_{1/2}$ 67.5%	$[3/2^{-}_{1}]p^{\Lambda}_{3/2}$ 27.1%	$[5/2^{-}_{1}](p_{3/2}p_{1/2})^{\Lambda}$ 2.7%

Our new concept is realized here in $^{10}_{\Lambda}$Be.

5. Two new calculations performed so as to make the situation clear

5(a) The recoilless ^{9}Be(K-,π-) $^{9}_{\Lambda}$Be reaction

schematic picture for easy understanding

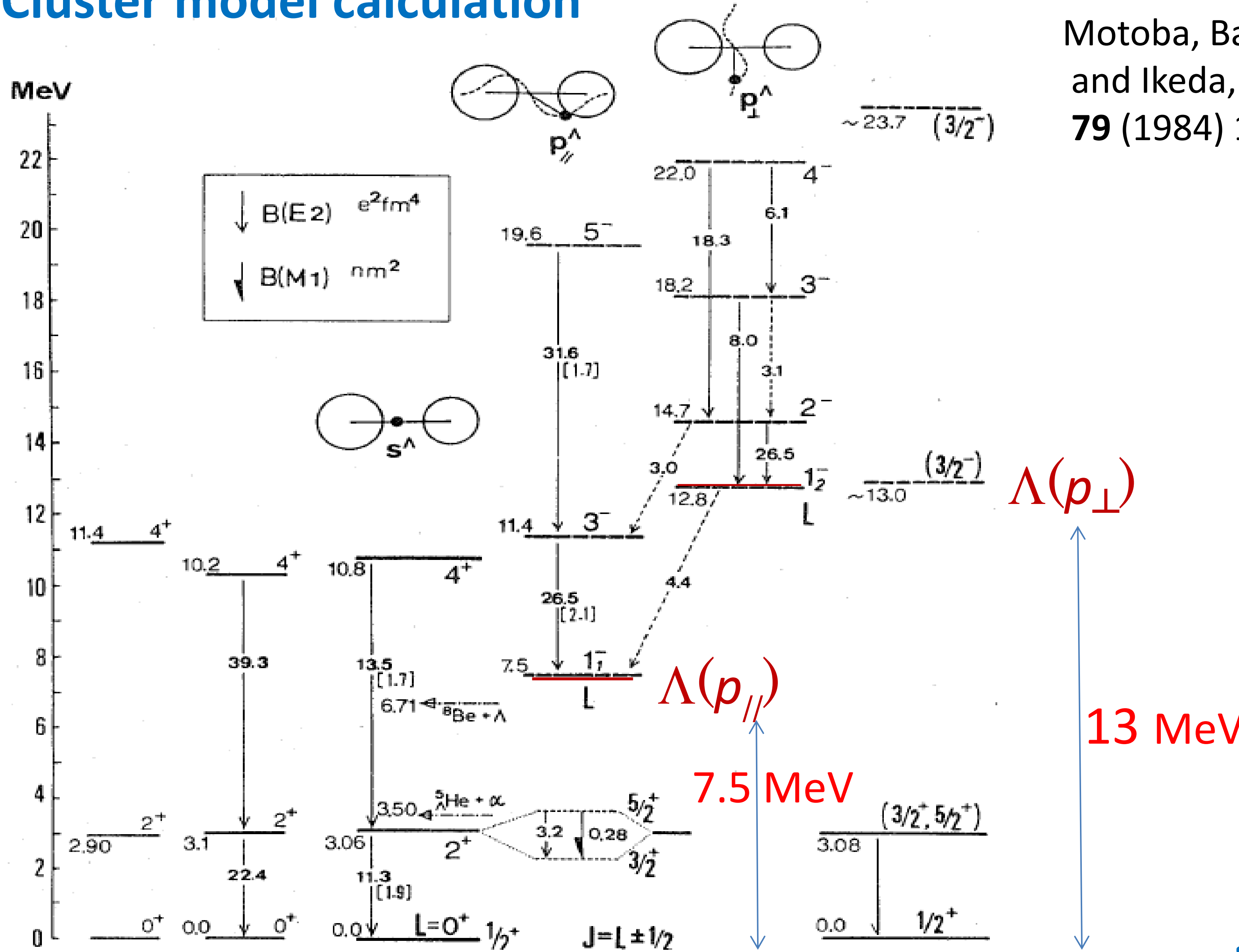


Core deformation causes energy splitting of *p*-state.

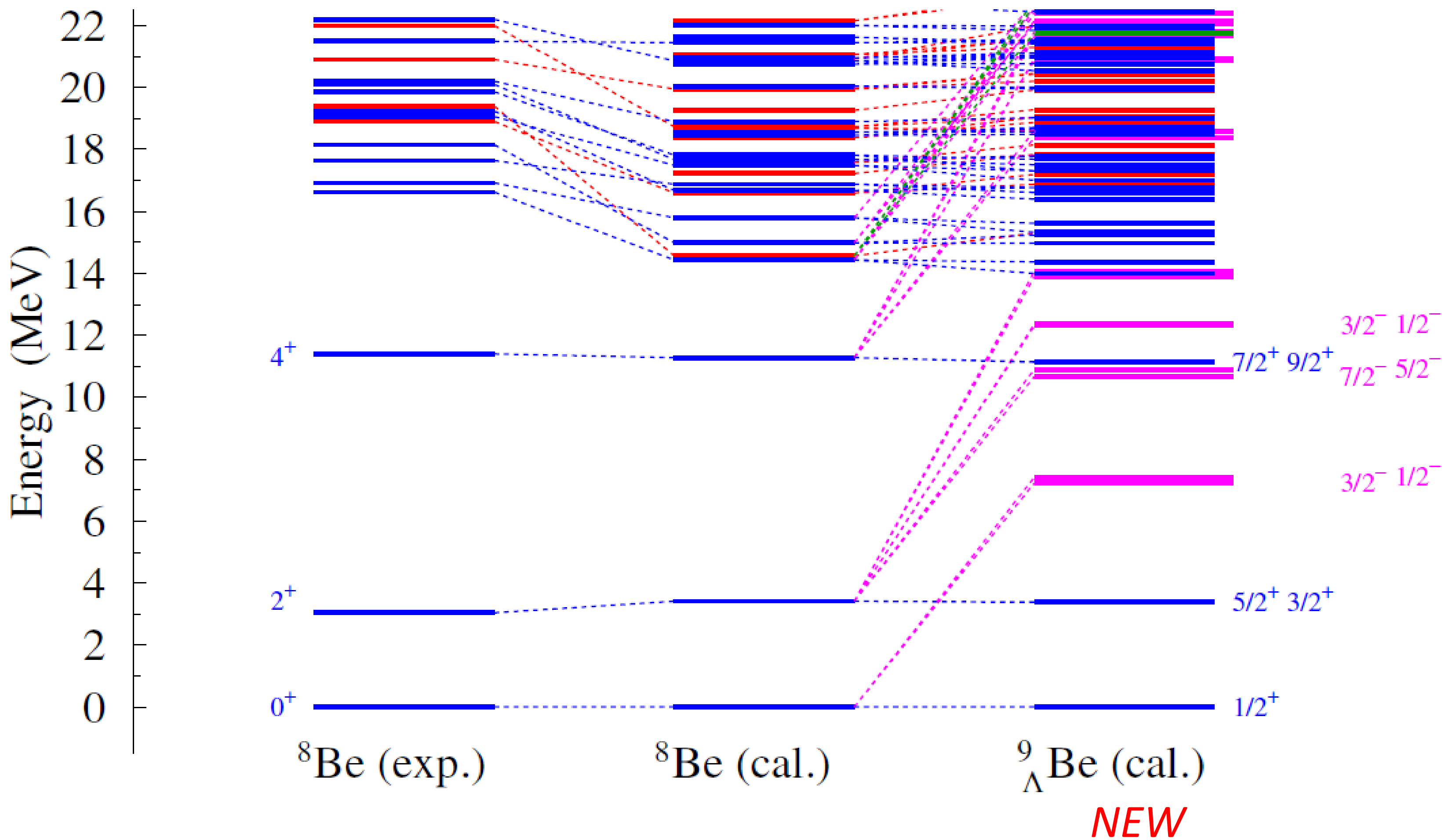
These structure characteristic was shown with a cluster model. (1983)

Cluster model calculation

Motoba, Bando, and Ikeda, P.T.P. **79** (1984) 189.

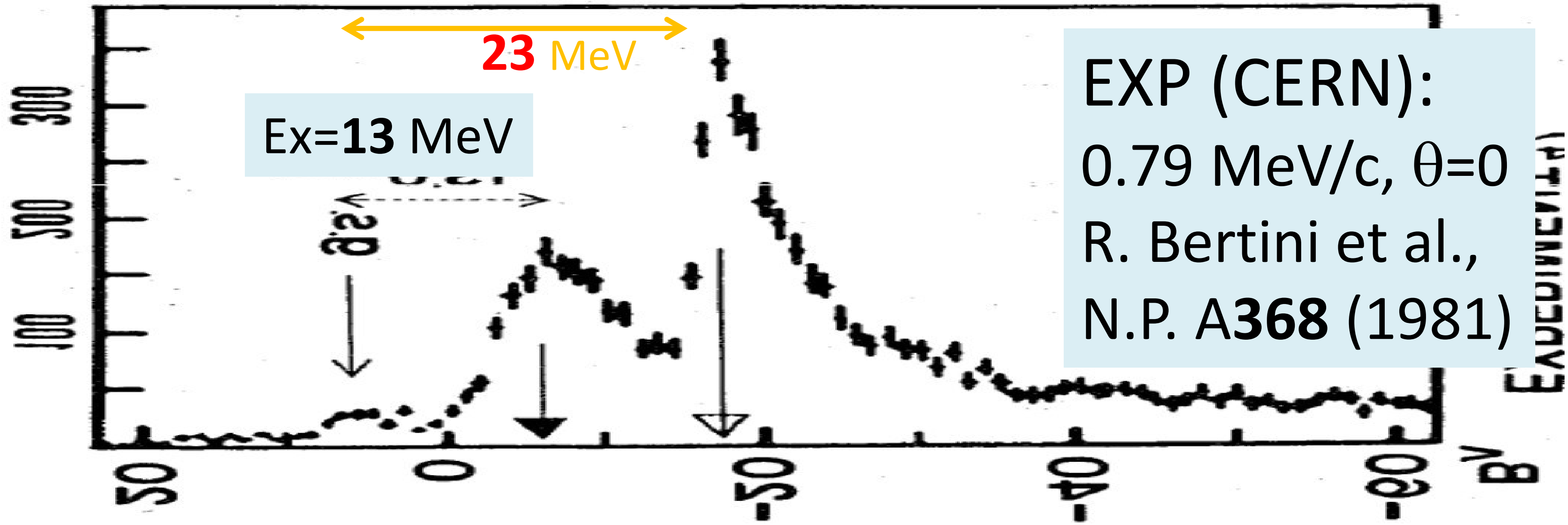


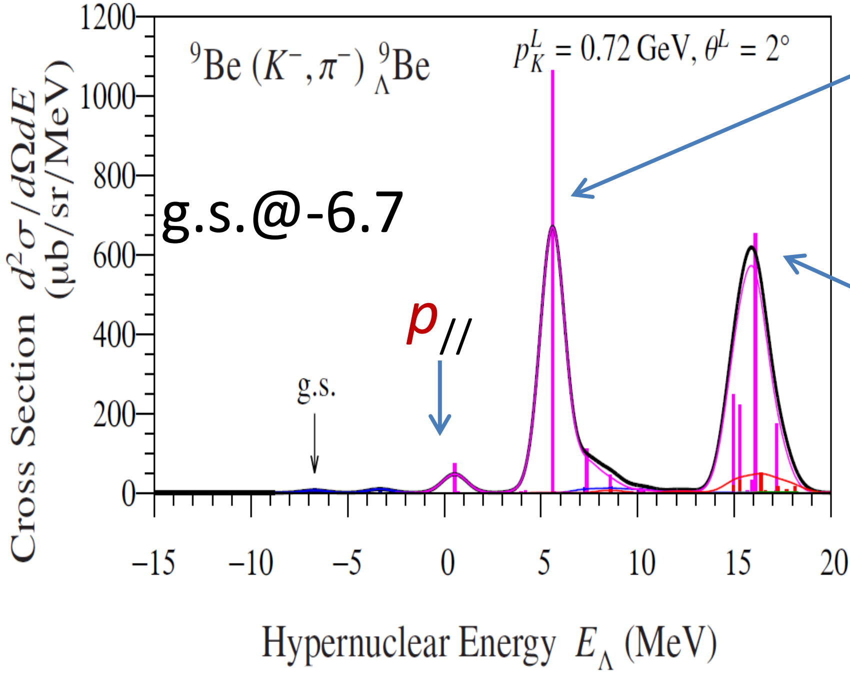
Energy levels of ^{8}Be and $^{9}_{\Lambda}$Be obtained with multi-configuration shell-model calculation



OUR IDEA: **Substitutional states among so many levels can be identified through the *recoilless* (K-,π-) reaction**

Recoilless (K$^-$,π^-) $^{9}_{\Lambda}$Be reaction: EXP vs. CAL





$p_\perp \rightarrow \Lambda(p_\perp)$ @Ex=12.3MeV

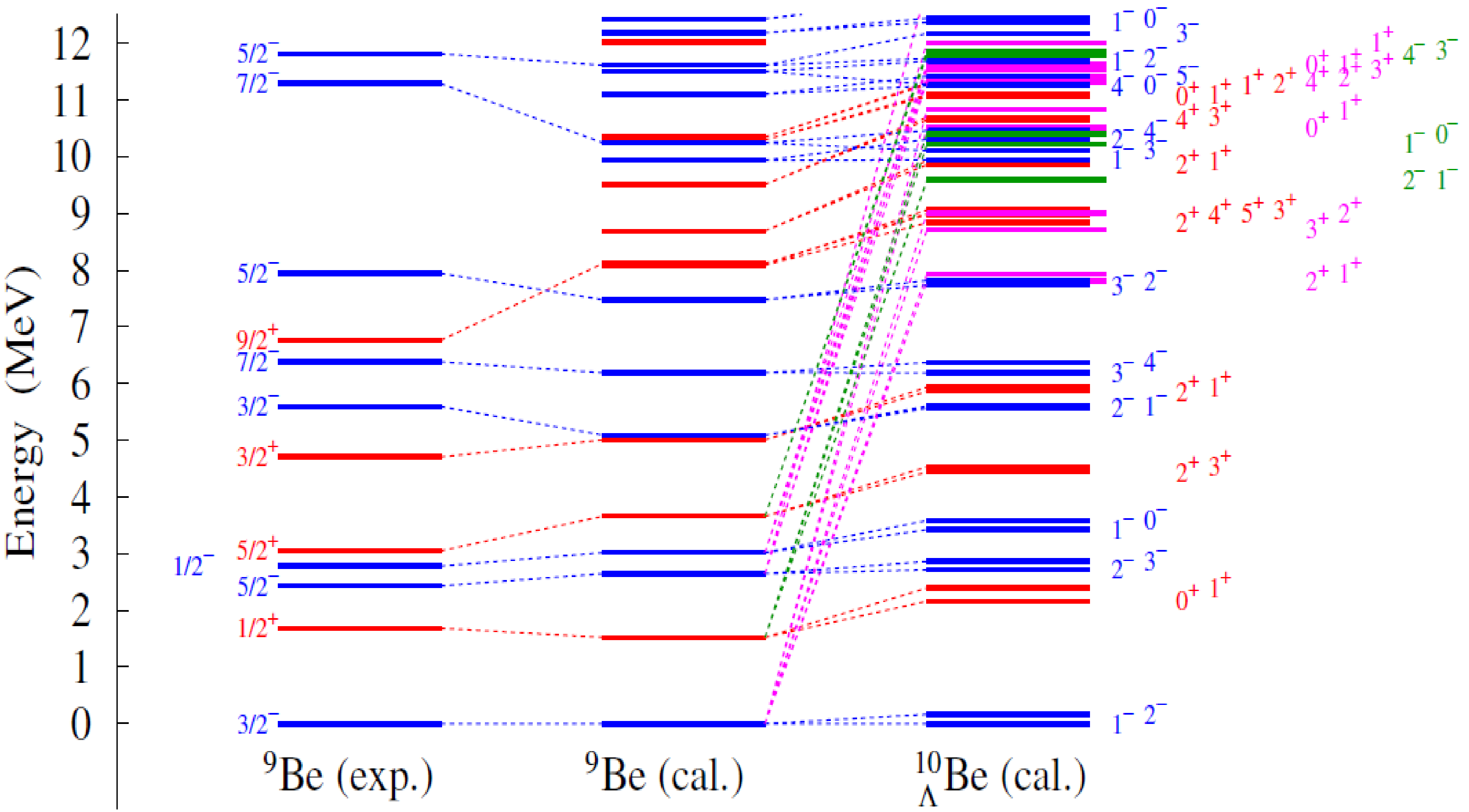
recoilless replacement of the surface **n**

$s^4,p^4 \rightarrow \Lambda(s,p)$

α-breaking deg. of freedom @ **22.8** MeV

Energy levels of ^{9}Be and $^{10}_{\Lambda}$Be

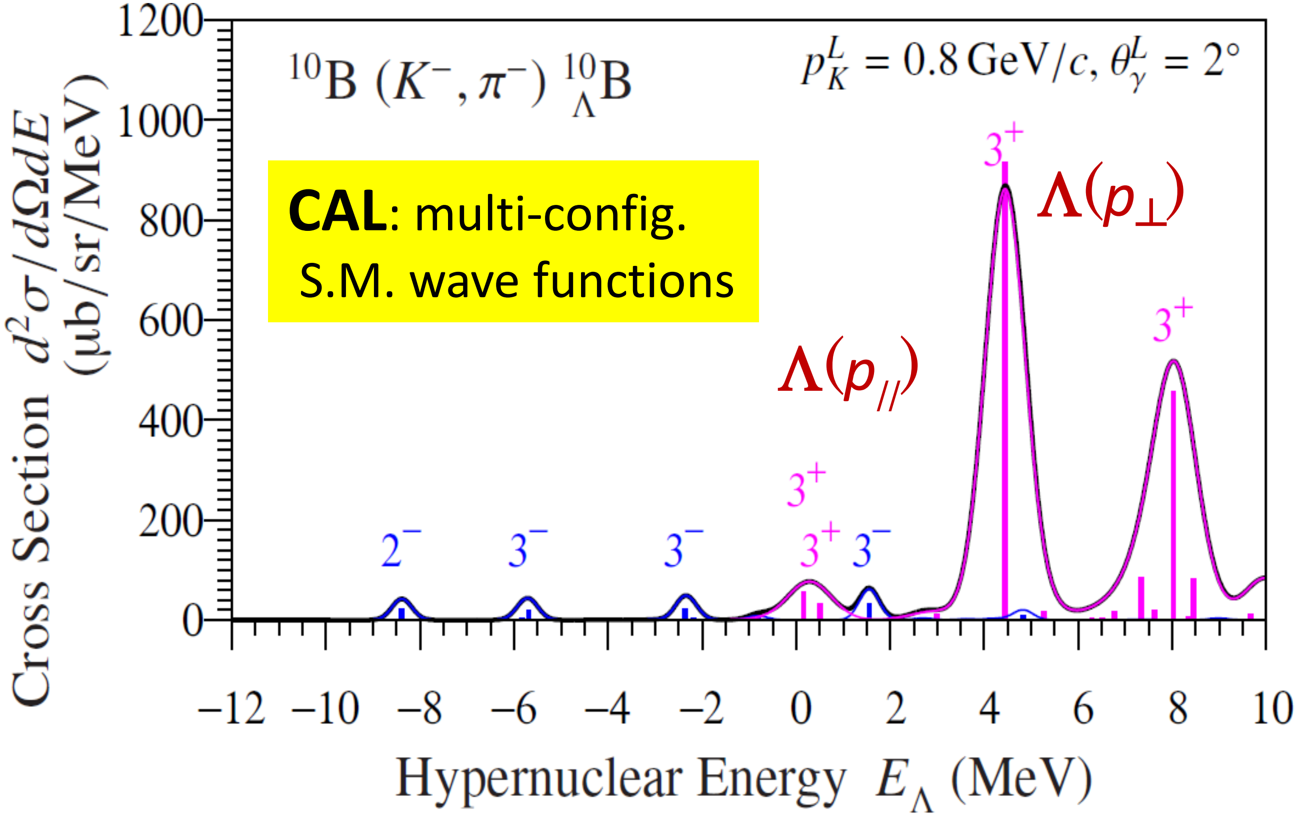
obtained with *multi-configuration* calculation



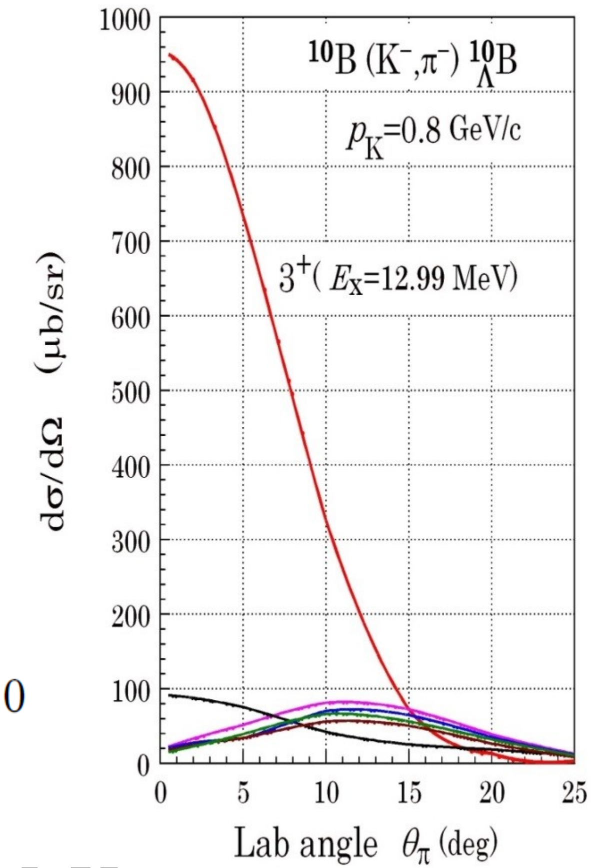
OUR IDEA: Substitutional states among so many levels can be identified through the *recoilless* (K-,p-) reaction

5(b) The recoilless ^{10}B(K-,p-) $^{10}_{\Lambda}$B reaction to identify the $\Lambda(p_\perp)$ energy

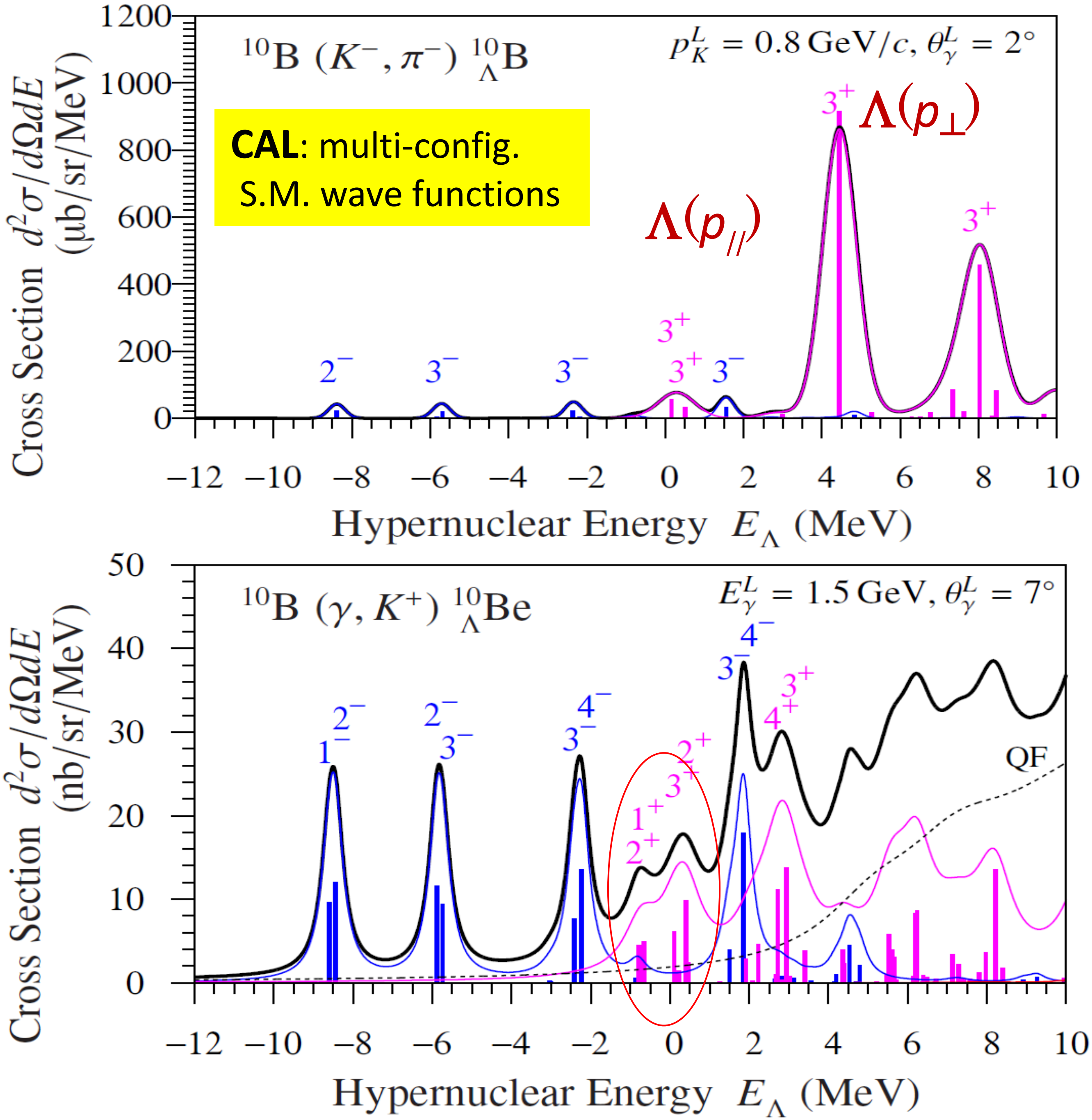
(K^-,π^-) reaction on $^{10}B(3^+)$=“αα”+p+n with recoilless condition ΔL=ΔS=0



typical ΔL=0 and ΔS=0



$p,n(p_\perp) \rightarrow \Lambda(p_{//})$@**8.7**MeV, $\Lambda(p_\perp)$@**13.0**MeV



CONCLUDE:
$\alpha\alpha$-like core deformation causes splitting of Λ p-states, then low-energy $\Lambda(p_{//})$ can mix with ^{9}Be(J^+)$\Lambda(s)$.

These parity-mixed w.f. at $E_\Lambda \approx 0$ MeV can explain the extra peak #a.

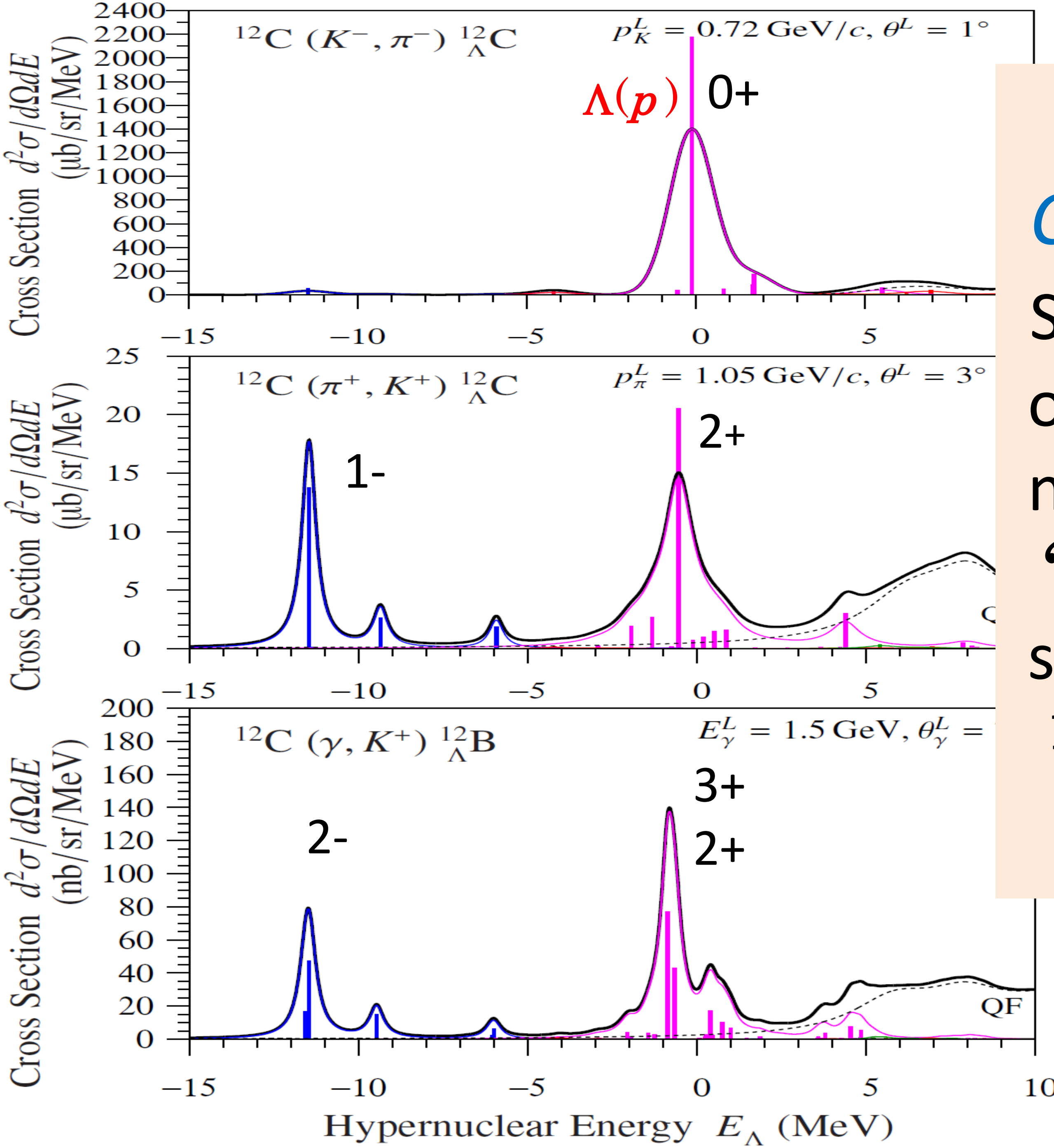
Conclusion-1. Mechanism of core-parity mixing mediated by the Λ hyperon is based on

REASON: ($\alpha\alpha$-like) **core nuclear deformation** causes

- → strong coupling between *p*-state Λ and core deformation (rotation) is realized in $^{9,10}{}_{\Lambda}\mathrm{Be}$ and $^{10}{}_{\Lambda}\mathrm{B}$.
- → Λ *p*-state splits into $\Lambda(p_{//})$ and $\Lambda(p_{\perp})$
- → the lower $\Lambda(p_{//})$ comes down in energy and $^{9}\mathrm{Be}(J^{-}) \times \Lambda(p_{//})$ couples easily with $^{9}\mathrm{Be}(J^{+}) \times \Lambda(s)$.

Therefore, such new type w.f. (coupling) should appear in $^{9,10}{}_{\Lambda}\mathrm{Be}$ and $^{10}{}_{\Lambda}\mathrm{B}$ due to the core deformation.

but "not" in spherical systems (w/o enough deformation).



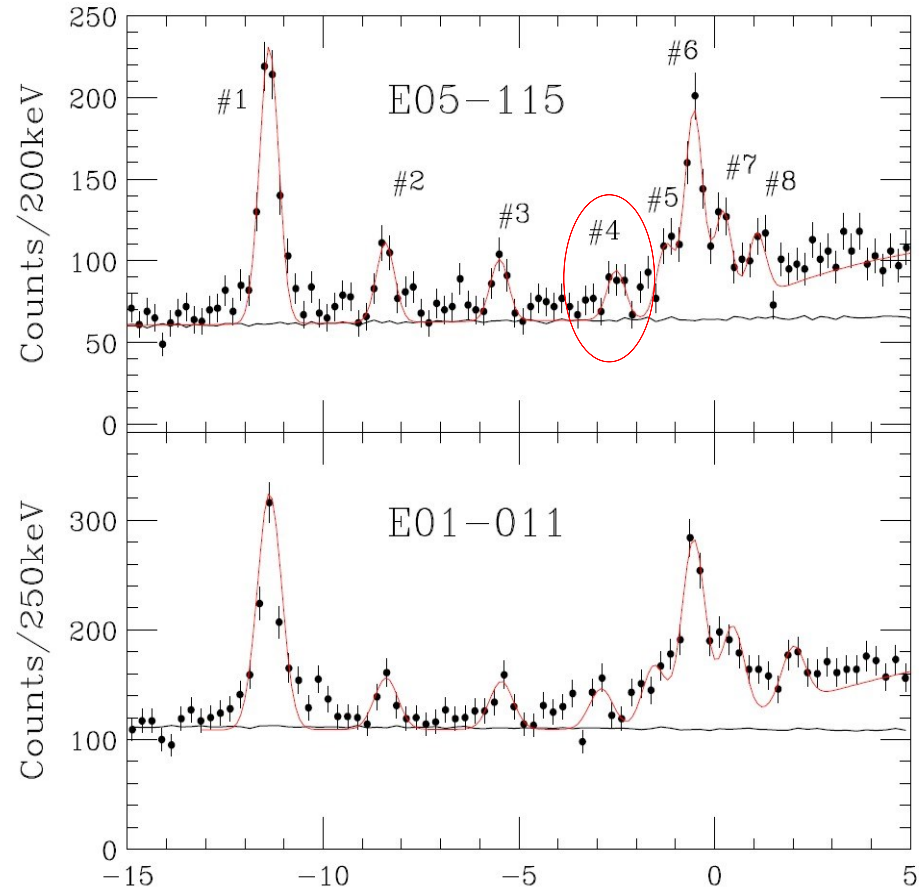
Conclusion-2.

Such new type of mixing might not occur in "spherical" systems such as $^{12}{}_{\Lambda}B$, $^{12,13}{}_{\Lambda}C$

A concluding remark: A new question if the extra peak #4 in Hall C exp. can survive in future exp. w/ better statistics.

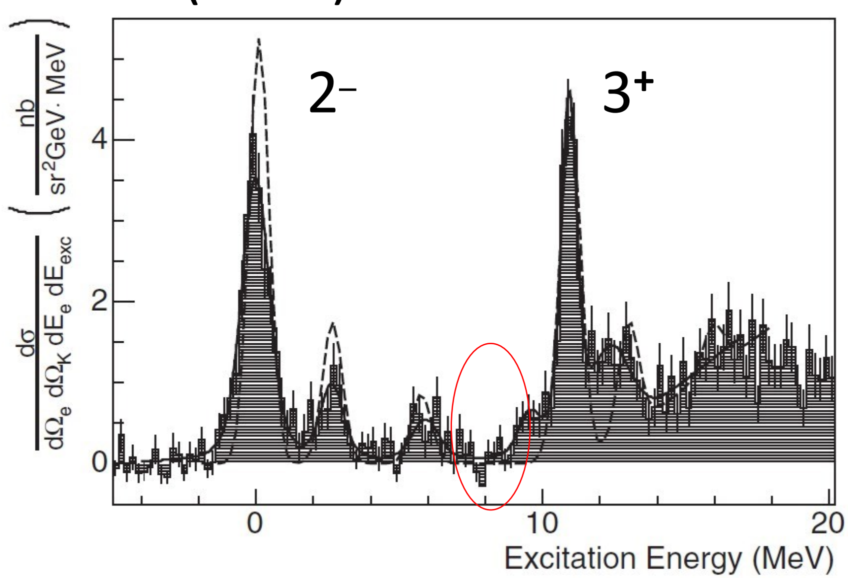
cf. Hall A spectrum

Hall C: L. Tang et al., PRC 90 (2014) **ΔE=0.54** MeV



$^{12}C(e,e'K^+)\ ^{12}{}_{\Lambda}B$

Hall A: M. Iodice et al., PRL 99 (2007) **ΔE=0.67** MeV



$[p^{-1}p^{\Lambda}]\Delta L=2, \Delta S=1; \Delta J=3$

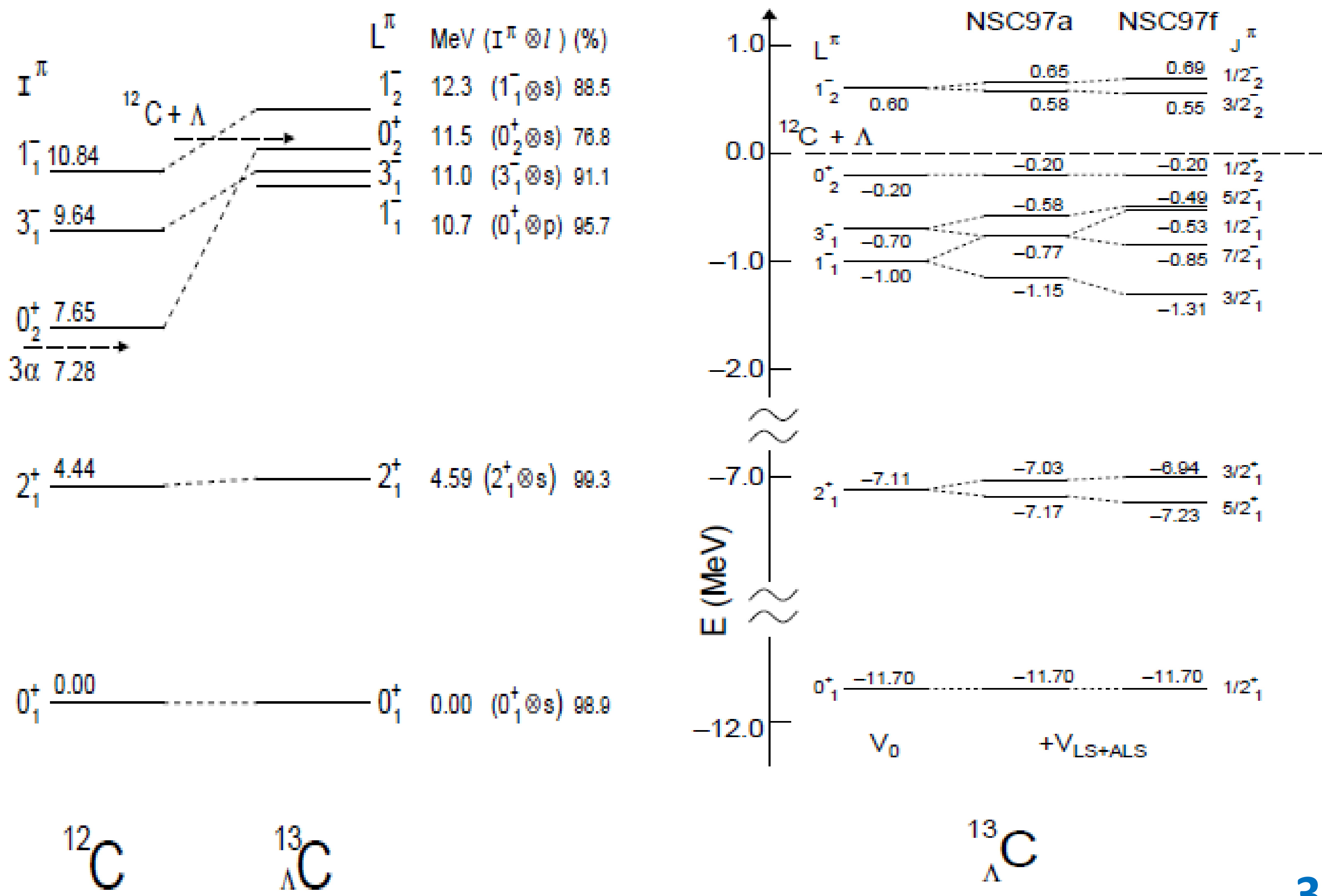
Conclusion-3. A characteristic and dynamical coupling between a hyperon and deformation (rotation) is applicable to other hypernuclei.

Emphasize: The finding of peak #**a** in ^{10}**B**(e,e'K^{+})$^{10}{}_{\Lambda}$**Be** is a novel evidence for genuine hypernuclear w.f. with parity-mixing realized in "deformed" hypernuclei.

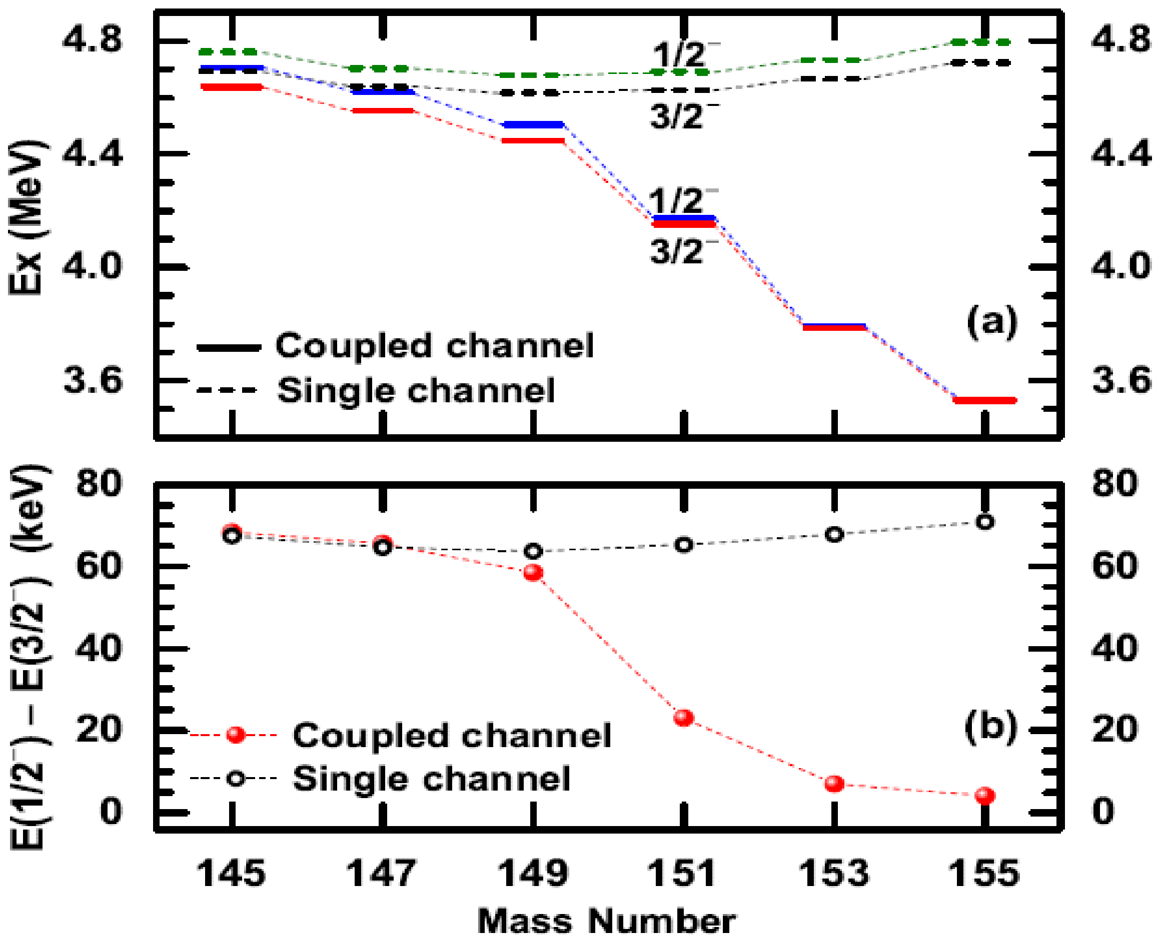
Emphasize: The s. p. energies of hyperon for l >0 should be extracted only from hypernuclei with a (nearly) spherical core.
(free from strong rotational coupling).

Appendix-1: $^{13}_{\Lambda}C$ case

Hiyama, Kamimura, Motoba, Yamada, Yamamoto, PRL 85 (2000)



Appendix-2: Transition from spherical to rotational characters in low-lying $^{145\text{-}155}{}_{\Lambda}\mathrm{Sm}$ isotopes: E(1/2-) and E(3/2-)



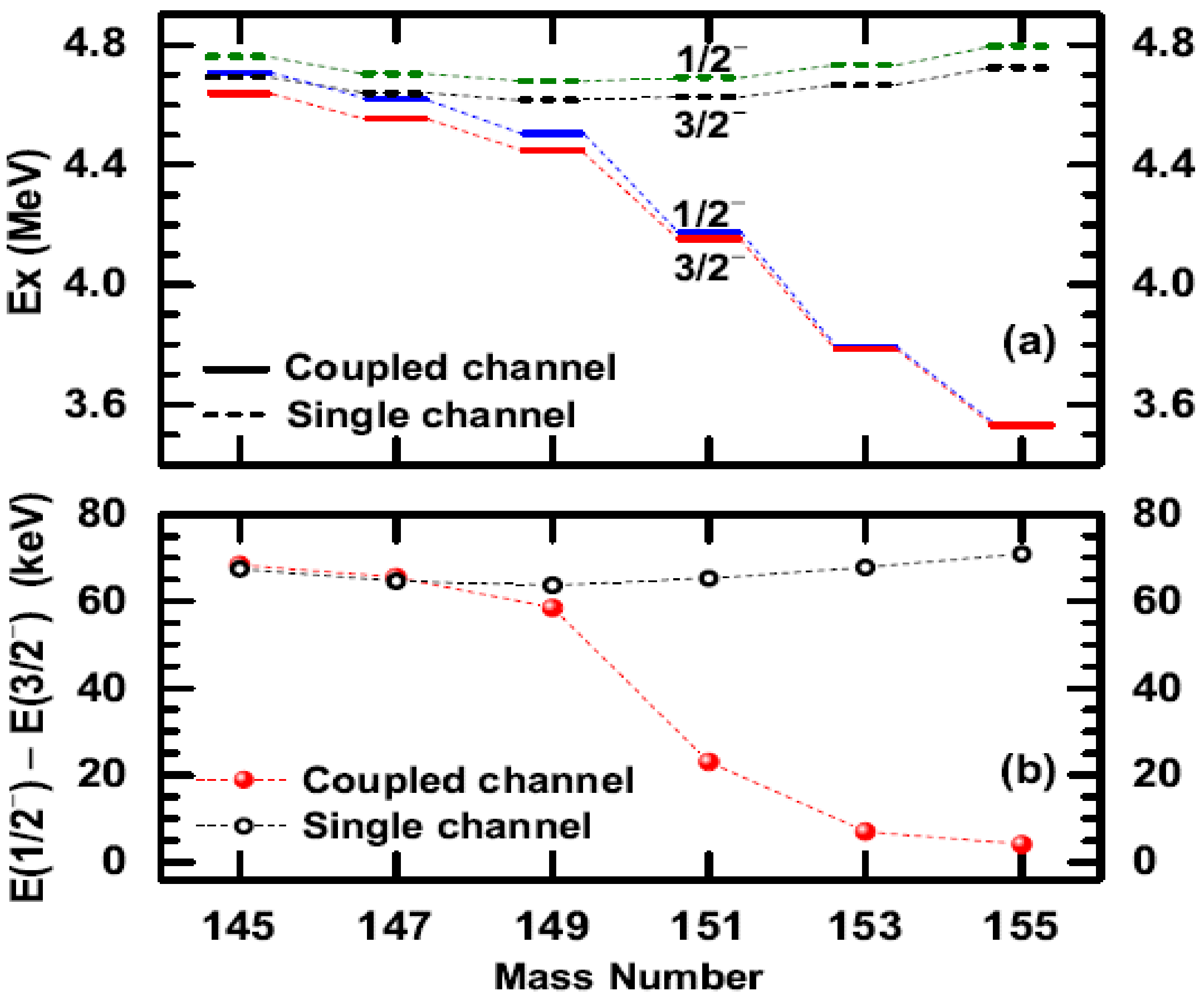
Spherical → rot.

cf. JM Yao's talk and

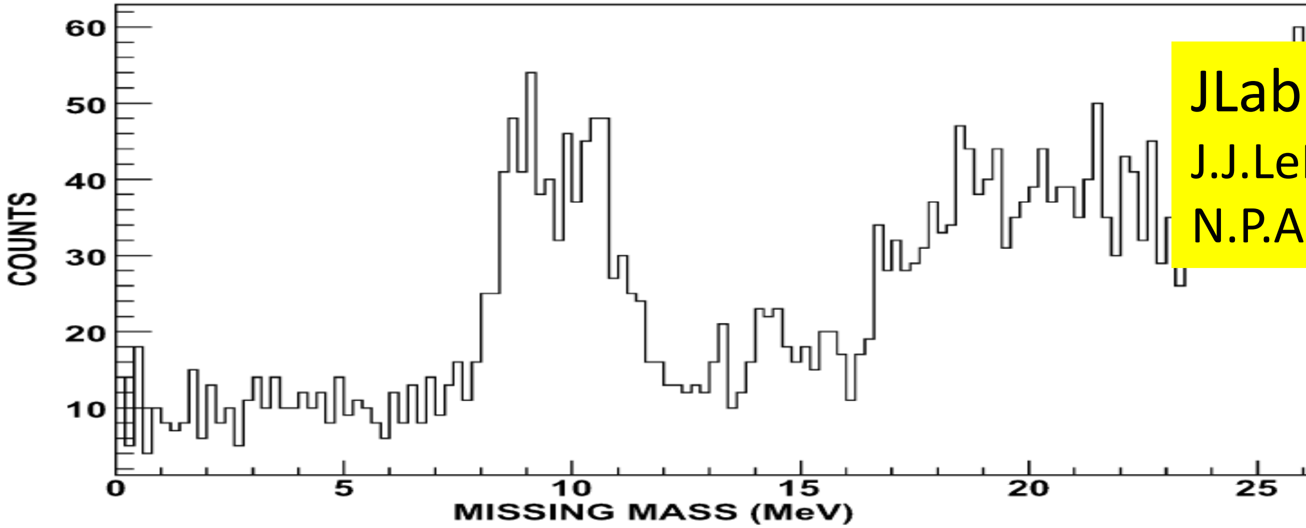
Mei, Hagino, Yao, Motoba, P.R.C **96** (2017)

$E(1/2_1^-)$ and $E(3/2_1^-)$ in hypernuclear $_\Lambda$Sm isotopes

Spherical core →→→ deformed

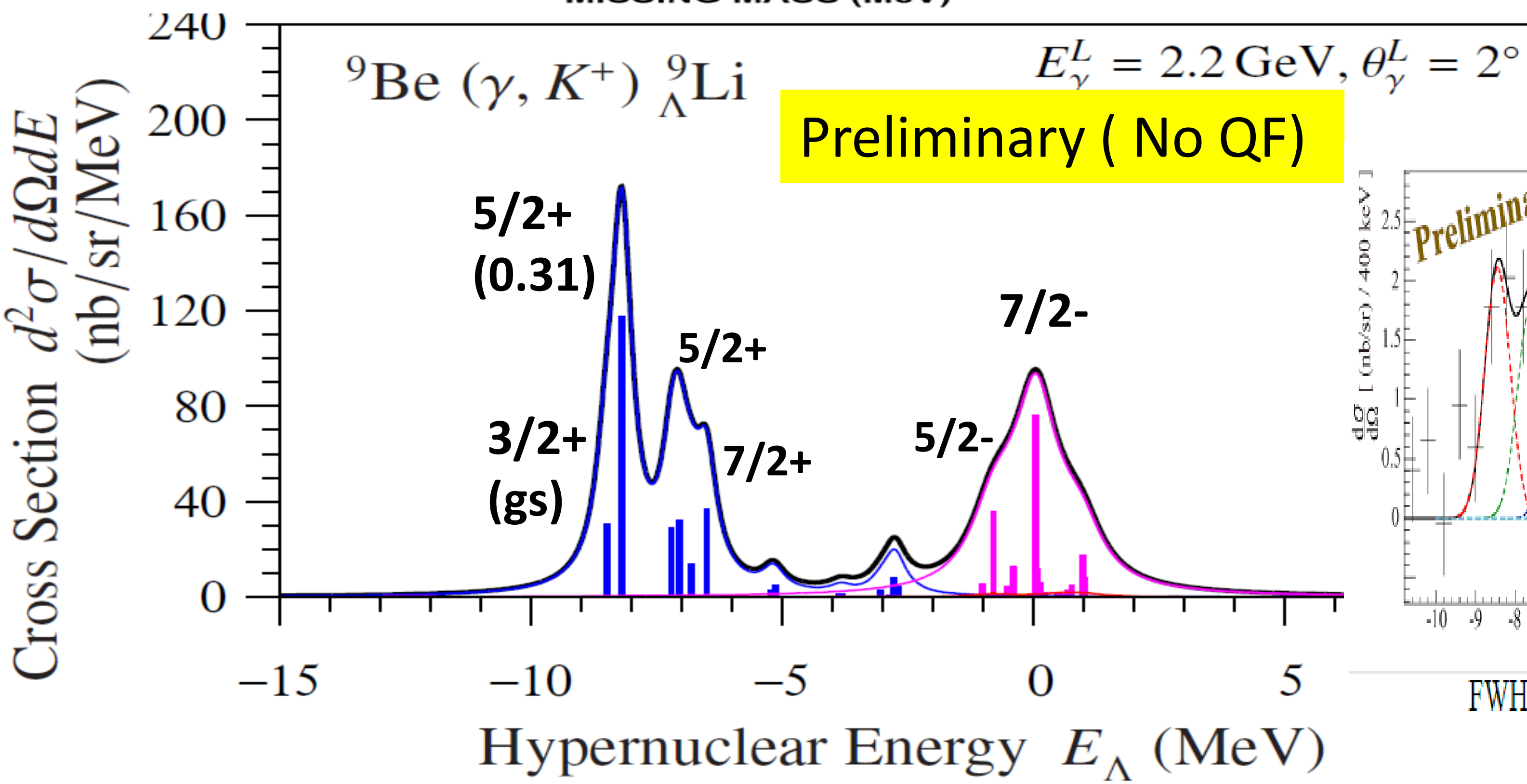


Buck-up slides follow:

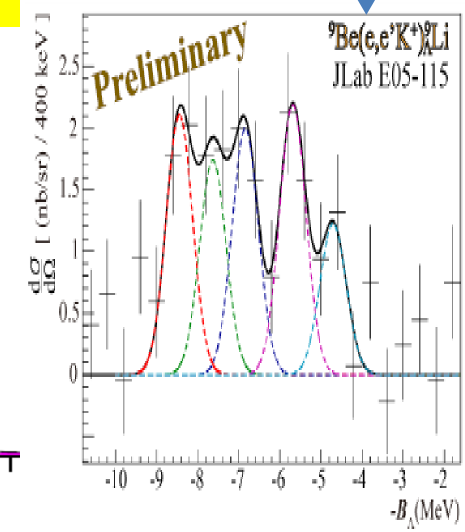


JLab Exp. (Hall A)
J.J.LeRose et al.,
N.P.A 804 (2008)116

Gogami's Talk(Tue)

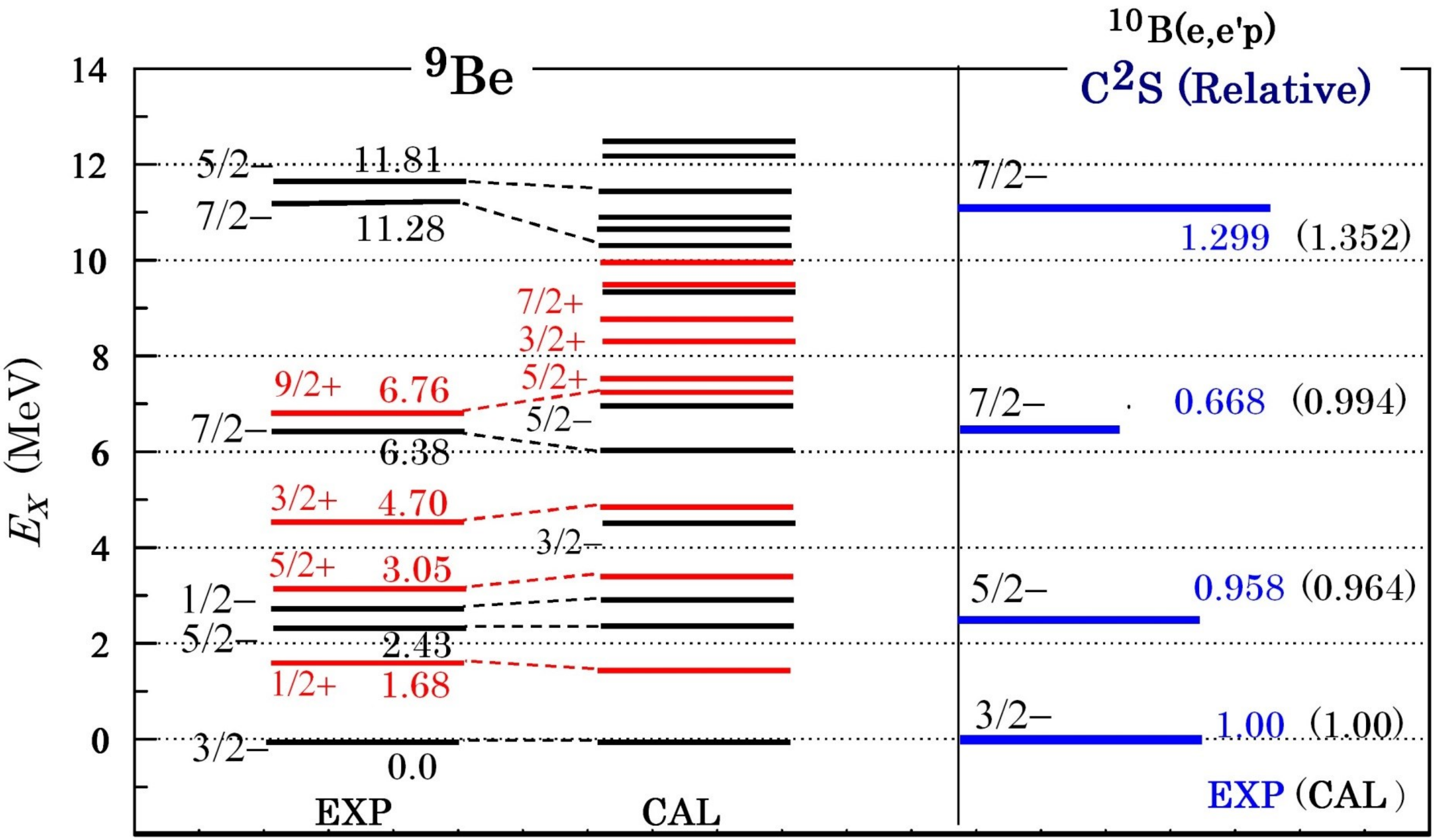


Preliminary (No QF)



FWHM ≅ 760 keV

Proton-pickup S-factors



Experimental S-factors are in very good agreement.