p-shell Hypernuclear Structure and its Production Rates based on Parity-Mixing Model

K. Itonaga (Gifu University)
A. Umeya (Nippon Institute of Technology)
T. Motoba (Osaka E-C University)

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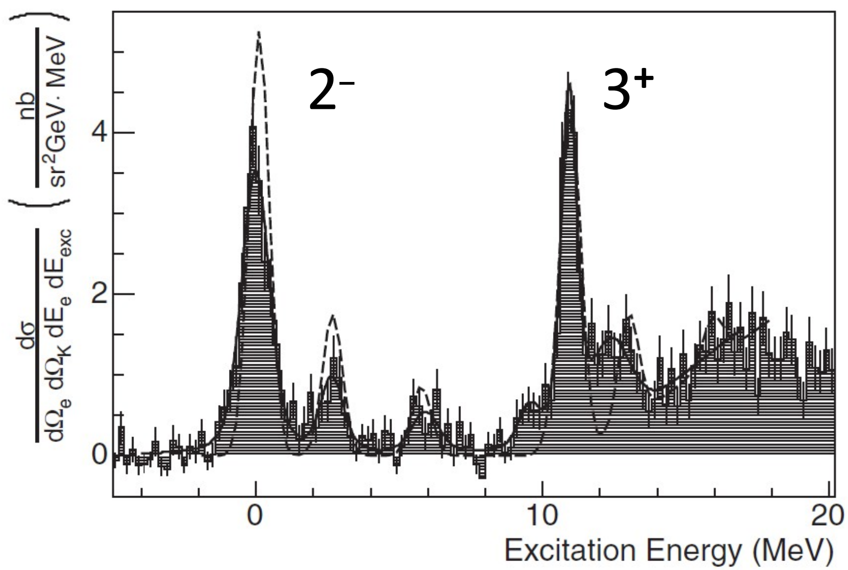
1. Introduction

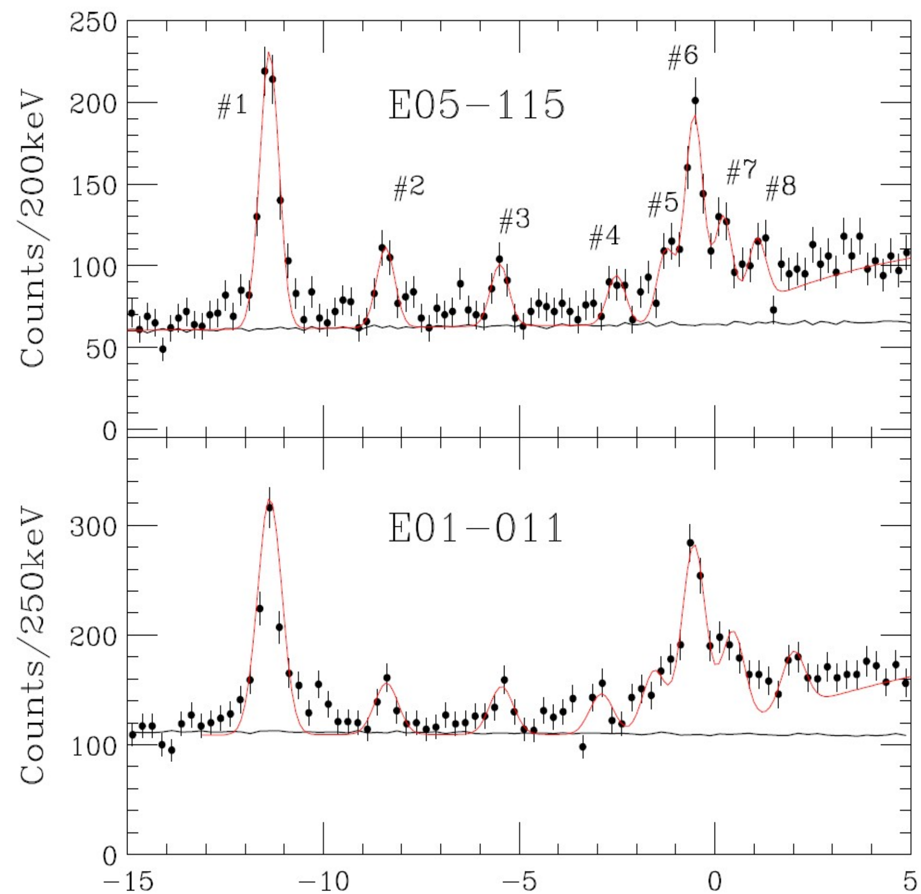
Success of high-resolution experiments at JLab

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

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

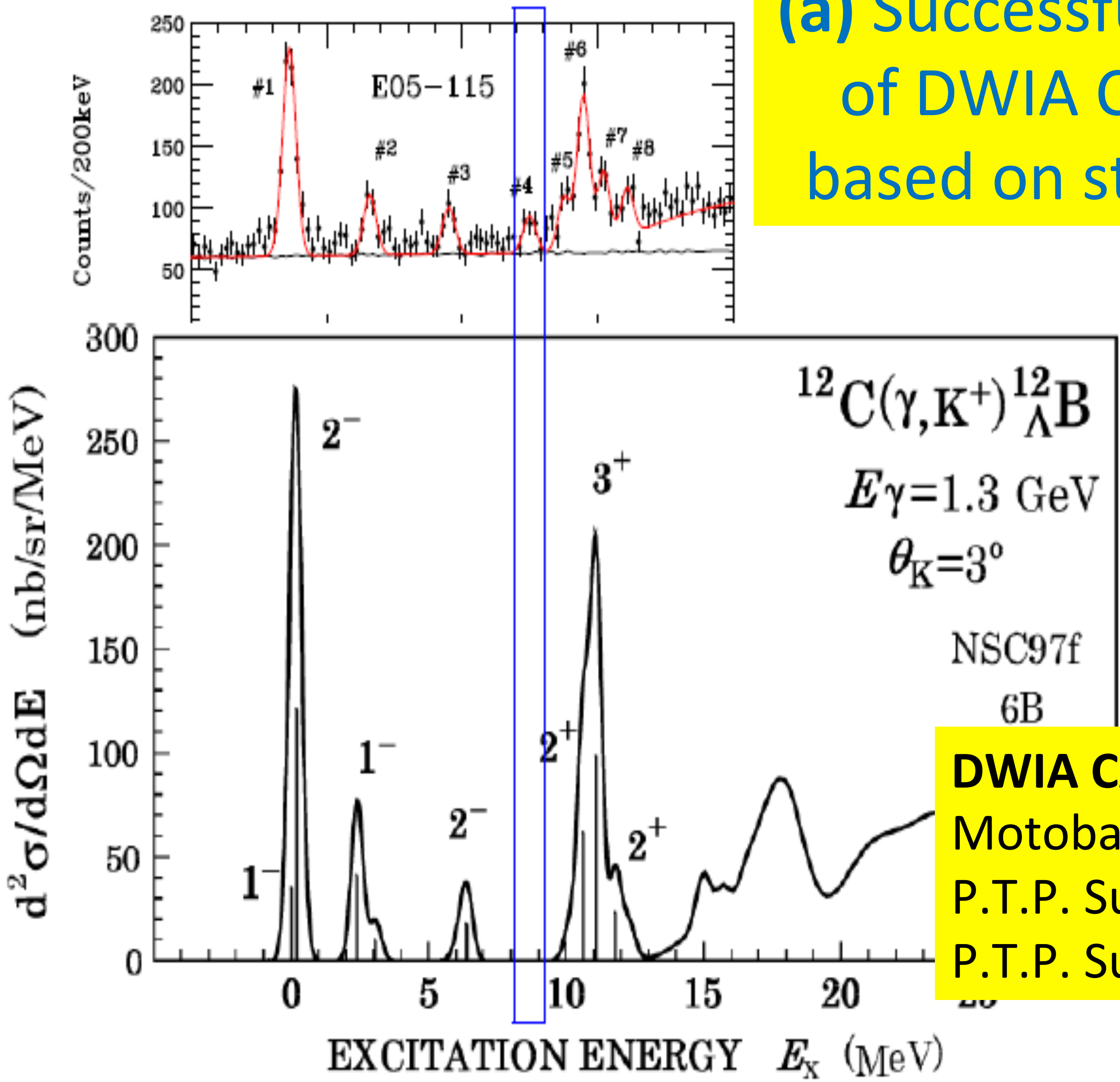


Hall C: L. Tang et al., PRC 90 (2014) **ΔE=0.54** MeV



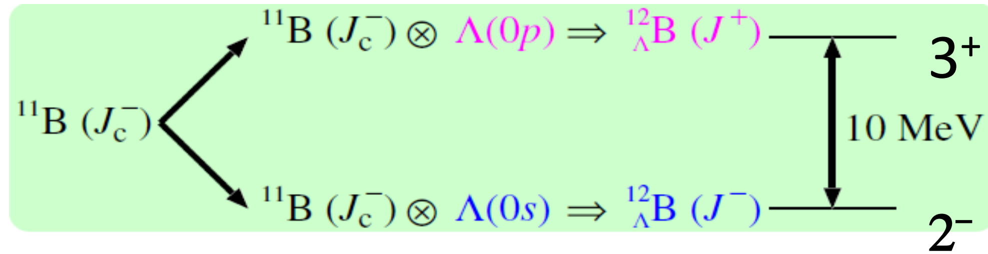
$[p^{-1}p^{\Lambda}]\Delta L=2, \Delta S=1; \Delta J=3$

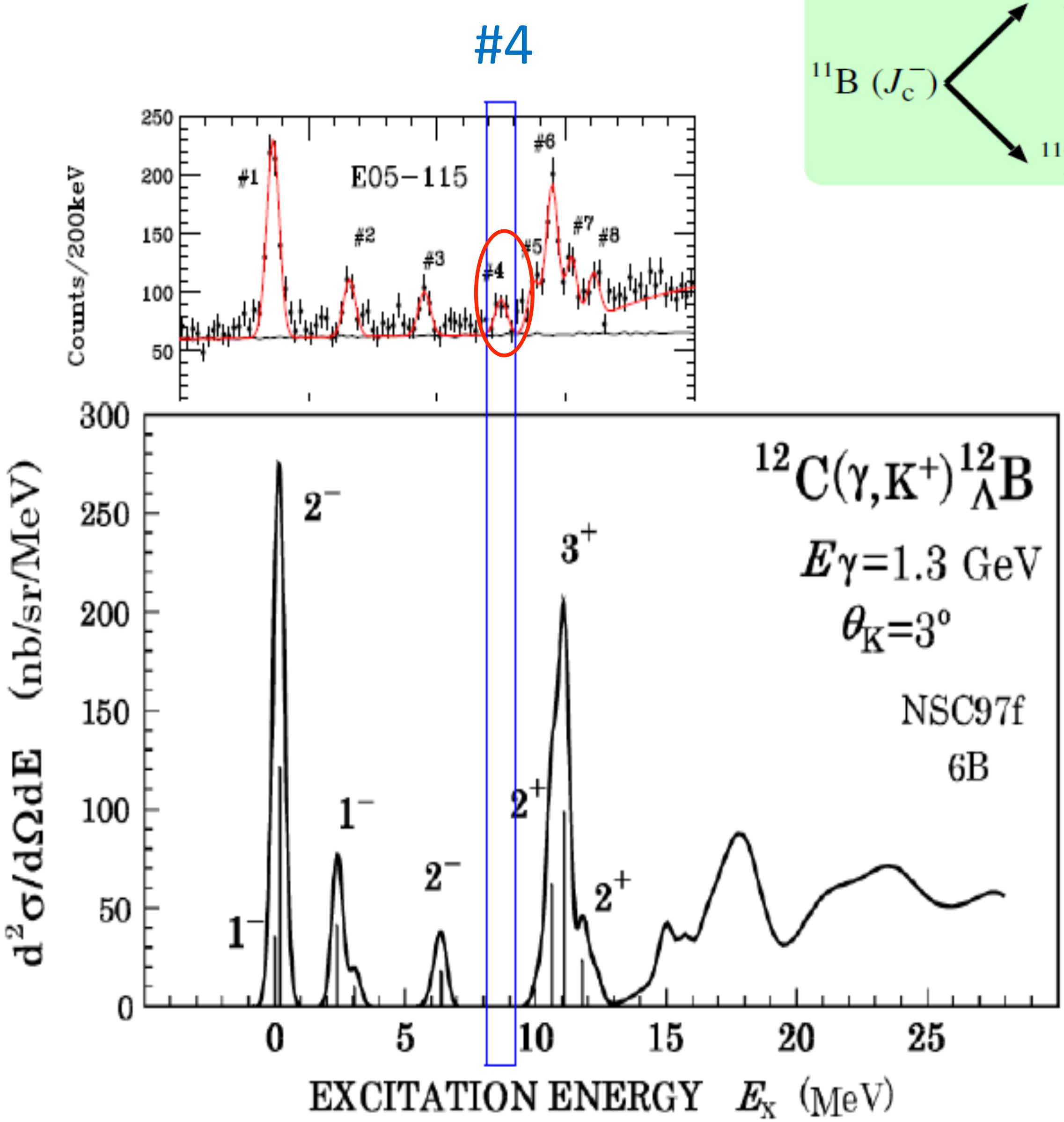
(a) Successful prediction of DWIA Calculation based on standard WF



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

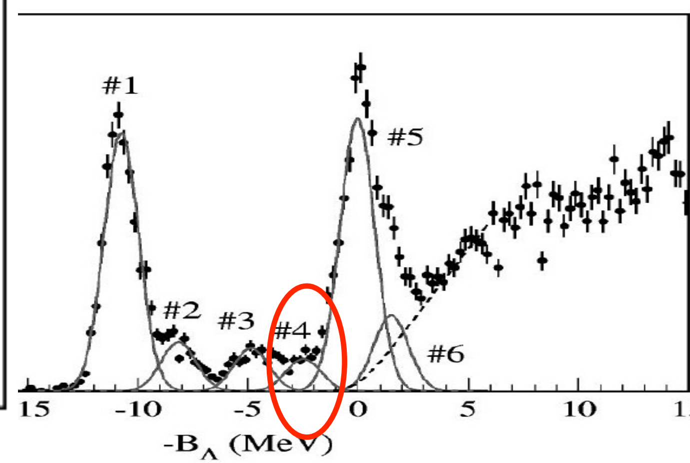
(b) But, **extra peak** such as #4 cannot be explained





Such extra peak has been observed also in (π+,K+). H. Hotchi et al., P.R. C 64 (2001).

ΔE=1.45 MeV



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

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

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

E05-115 Experiment [9] $\theta_{\gamma K} \approx 6.8°$				CAL: SLA [16] at $\theta_K = 7°$				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	

2. Extended theoretical treatment required ------ Concept and model -----

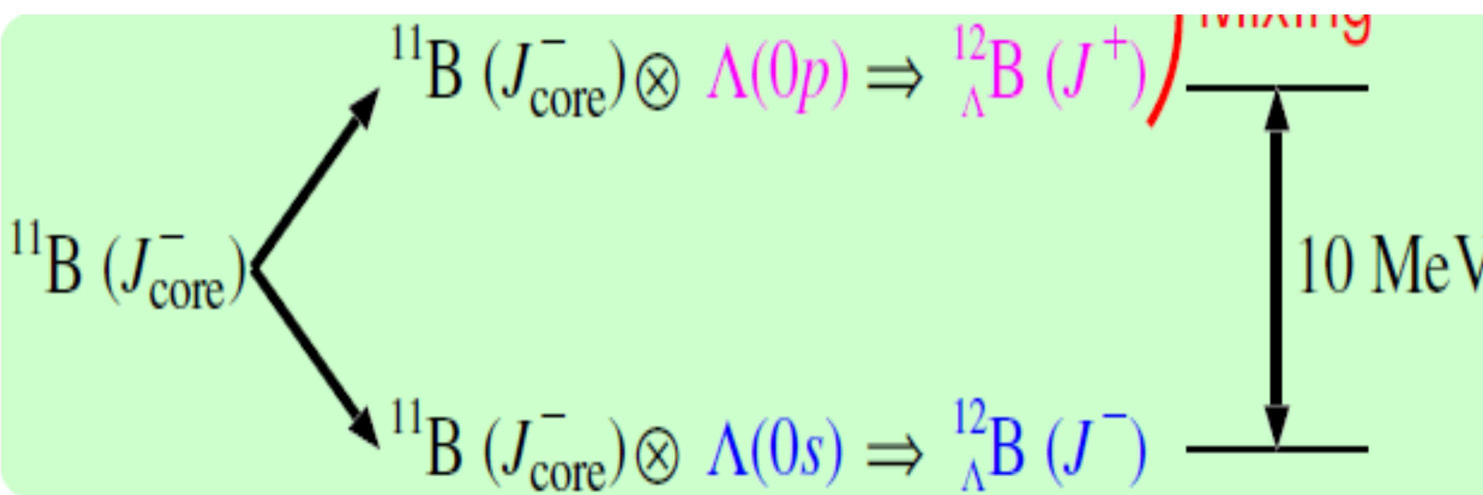
Standard configuration assumed so far:

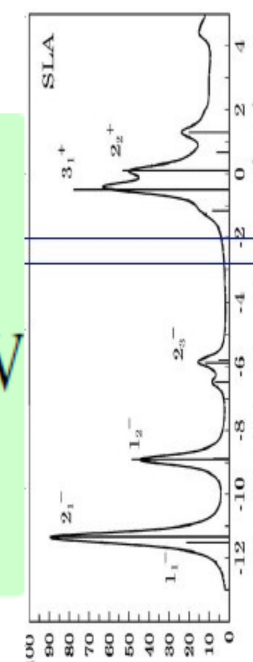
Model space for ^{11}B core

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

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

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





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

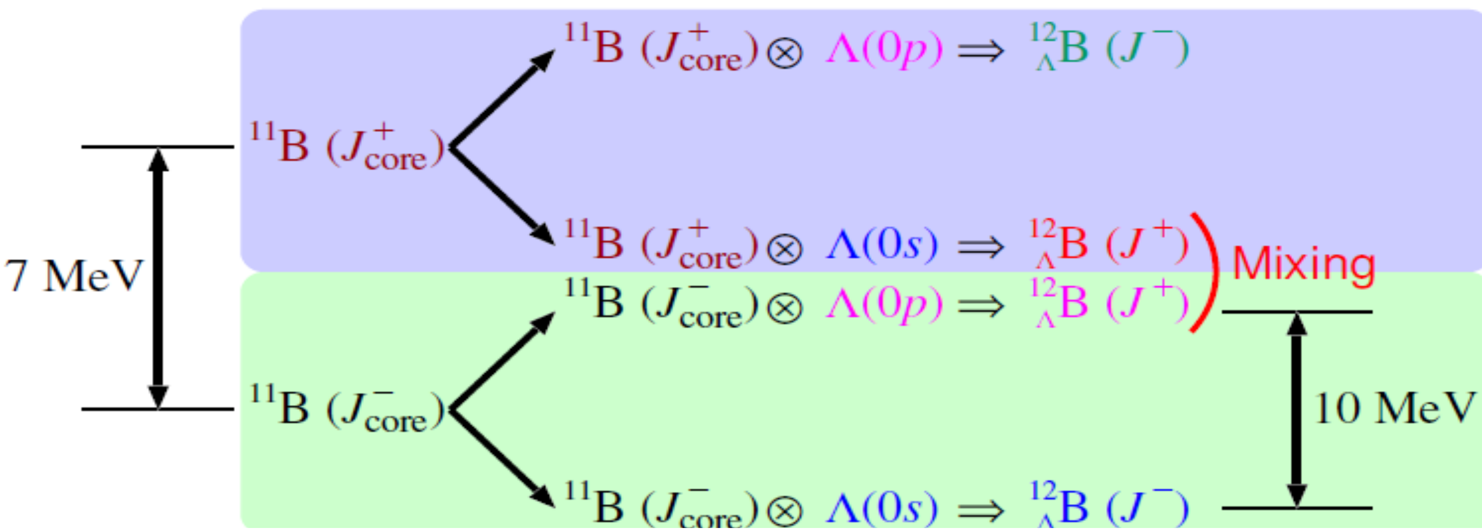
Extention (1) **$1p$-$1h$ core excitation is taken into account**

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

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

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

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



Config. MIX. Should occur

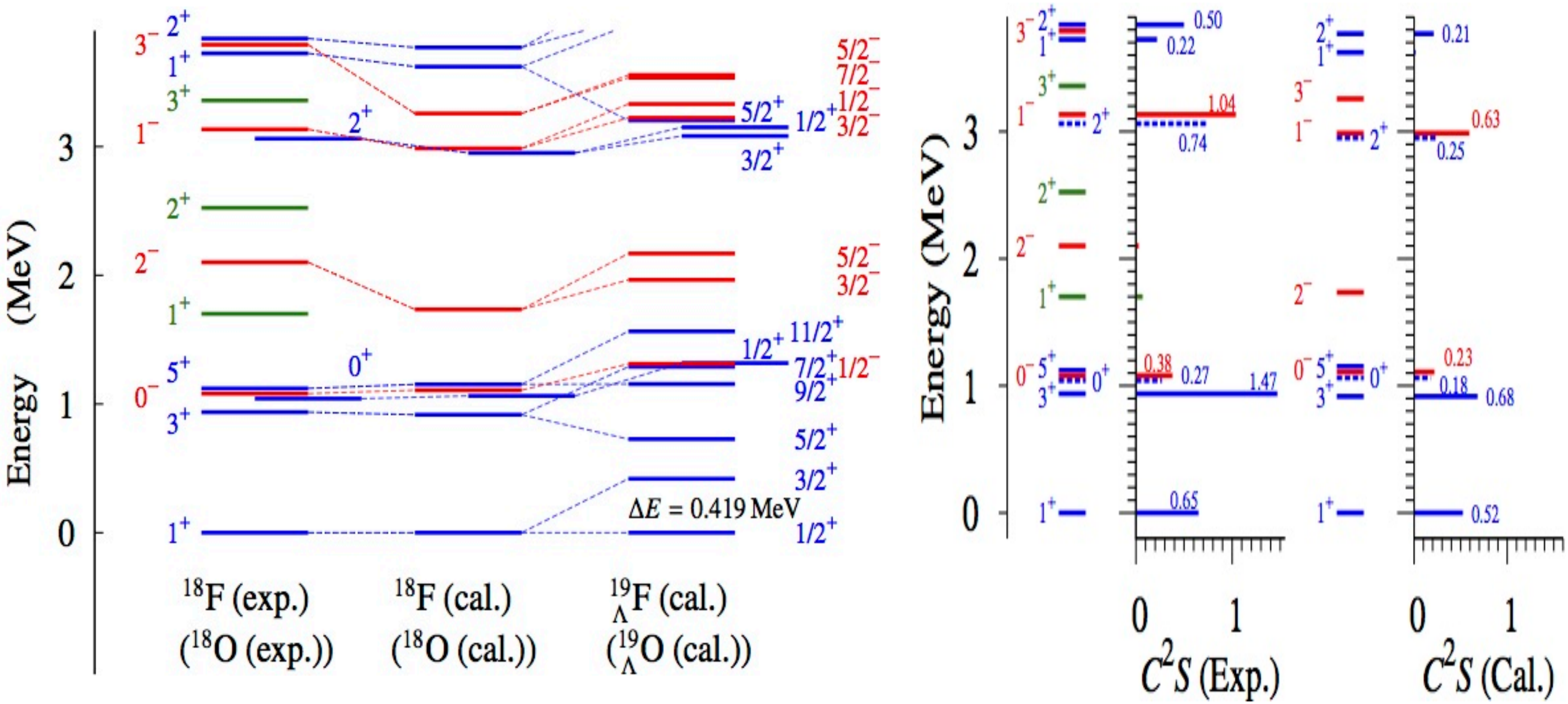
$$\varepsilon(0p^{\Lambda}) - \varepsilon(0s^{\Lambda}) \approx E(^{11}\mathrm{B}(J^{+}_{\rm core})) - E(^{11}\mathrm{B}(J^{-}_{\rm core}))$$

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

2-a) Application of the extention (1) to $^{19}_{\Lambda}$F hypernuclei

A. Umeya and T. Motoba, Nucl.Phys.A 954 (2016) 242.

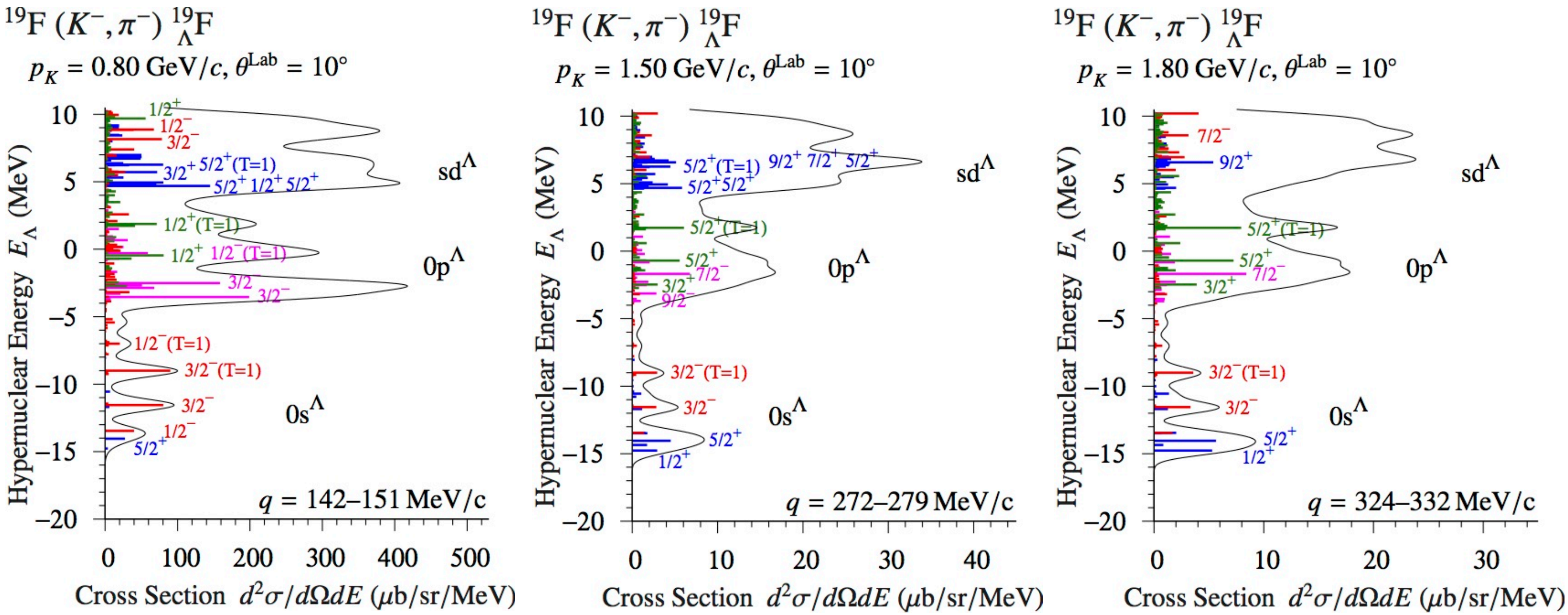
Energy levels and spectroscopic factors of n-pickup reaction from ^{19}F



Negative parity states ($J^-_{\rm core}$) of ^{18}F, which are constructed by $1p$-$1h$ states, exist in low-lying energy region.

Negative parity states (J^-) of $^{19}_{\Lambda}$F are constructed by $(0s)^4(0p)^{11}(sd)^3(0s^{\Lambda})$ and $(0s)^4(0p)^{12}(sd)^1(fp)^1(0s^{\Lambda})$ configurations.

Cross sections of ^{19}F(K^-, π^-) at different incident momemta

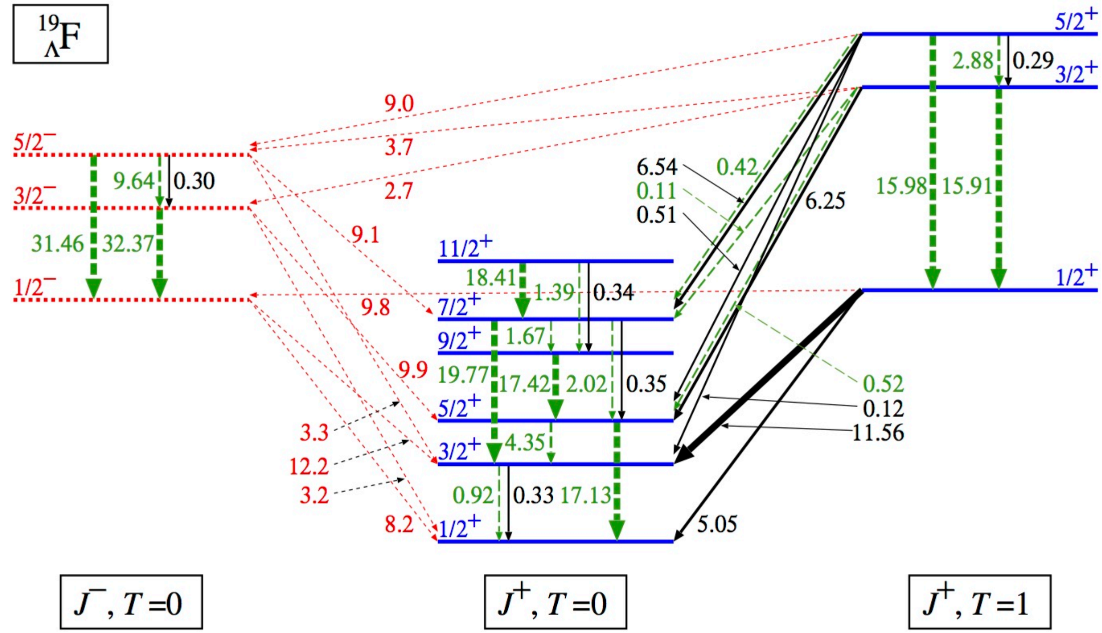


(a) $J^+{}_{\rm core} \otimes j^+{}_\Lambda$ (b) $J^+{}_{\rm core} \otimes j^-{}_\Lambda$ (c) $J^-{}_{\rm core} \otimes j^+{}_\Lambda$ (d) $J^-{}_{\rm core} \otimes j^-{}_\Lambda$

The microscopic DWIA calculations at high energy kaon momenta up to 1.8 GeV/c have been carried out for the first time.

The DWIA calculation at p_K=1.8 GeV/c correspond to the J-PARC E13 experiment [H. Tamura et al., Proceedings of HYP2015].

E2, M1 and E1 transitions of $^{19}_{\Lambda}$F are extensively estimated. The result E2(5/2+→1/2+) should be compared with J-PARC **E13** exp.



Accumulated production cross sections *Y* and *γ*-decay rates of $^{19}_{\Lambda}$F

J_i(T)	E_i	Y_i	J_f(T)	E_f	ΔE_{if}	branching	T
	MeV	μb		MeV	MeV	ratio	s^{-1}
3/2+(0)	0.419	125.0	1/2+(0)	0.000	0.419	1.000	4.24×10^{11}
5/2+(0)	0.727	120.5	1/2+(0)	0.000	0.727	0.989	4.28×10^{9}
			3/2+(0)	0.419	0.308	0.011	4.75×10^{7}
7/2+(0)	1.289	19.1	3/2+(0)	0.419	0.869	0.011	1.20×10^{10}
			5/2+(0)	0.727	0.561	0.989	1.08×10^{12}
1/2-(0)	1.311	265.1	1/2+(0)	0.000	1.311	0.681	2.93×10^{10}
			3/2+(0)	0.419	0.892	0.319	1.37×10^{10}

2-b) Extensions of both (1)+(2) for $^{12}{}_{\Lambda}$B

our new theoretical challenge

"parity-mixing mediated by Λ"

(a new concept seen only in hypernucleus)

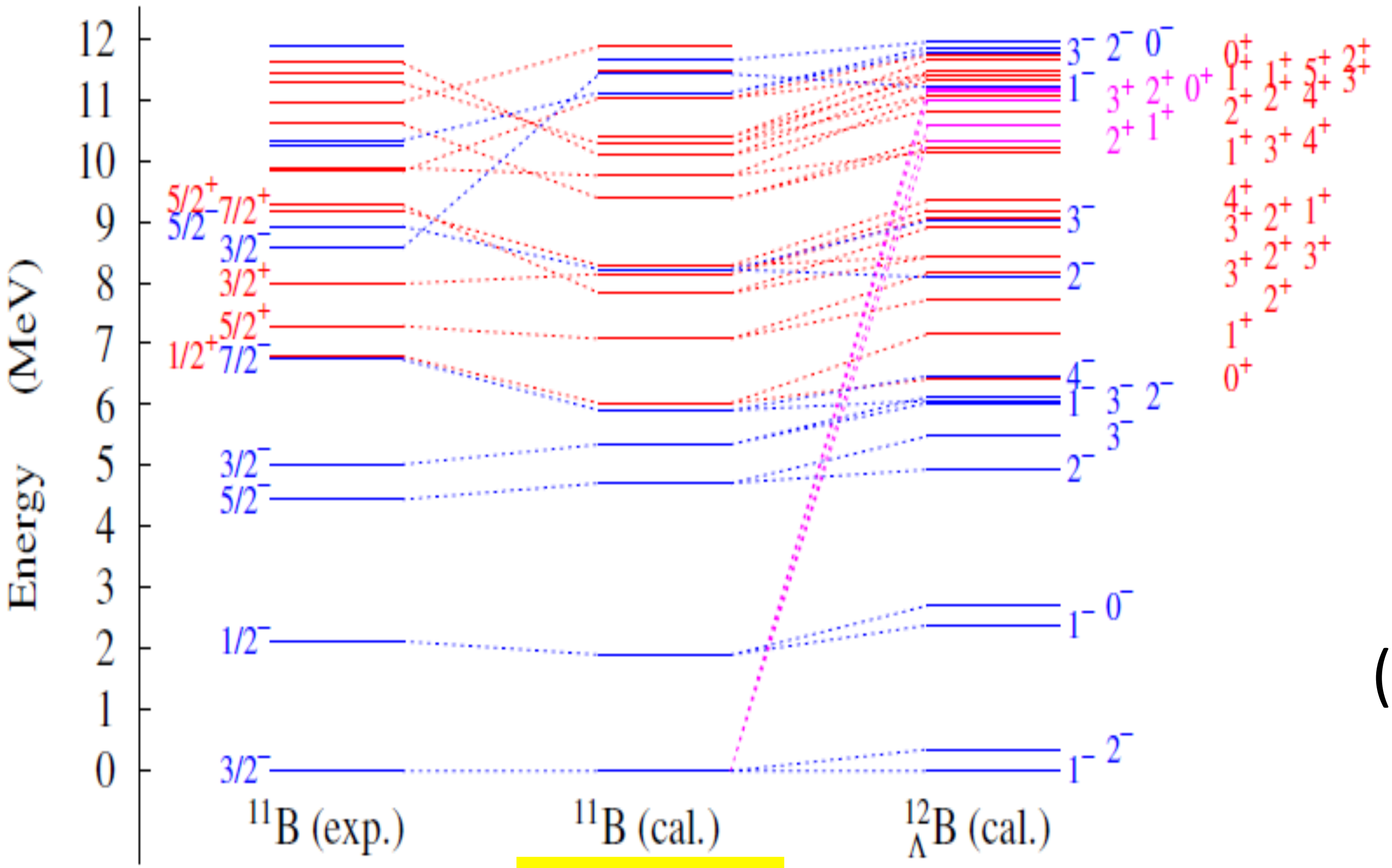
$$^{12}{}_{\Lambda}\mathrm{B}(J_H^-) = \{ ^{11}\mathrm{B}(J_C^-)_0 \times \Lambda_s \}^{(0)} + \{ ^{11}\mathrm{B}(J_C^+)_1 \times \Lambda_p \}^{(2)}$$

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

→ Energy levels, Proton-pickup S factors,

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

Obtained energy levels for ^{11}B, $^{12}{}_{\Lambda}$B



(p_{Λ} dominant, but mixed)

(s_{Λ} dominant, but mixed)

(s_{Λ} states)

Spurious CM removed

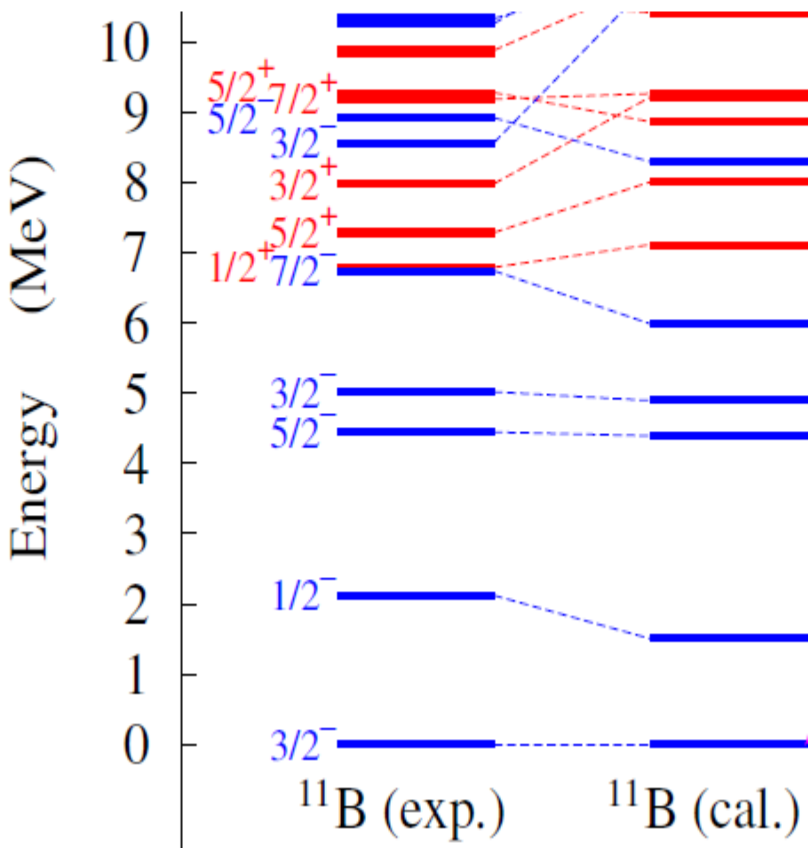
Parity-mixed multi- config.

J^- states (blue lines) mainly consist of $^{11}\mathrm{B}(J^-_{\mathrm{core}}) \otimes \Lambda(0s)$.

J^+ states (magenta lines) mainly consist of $^{11}\mathrm{B}(J^-_{\mathrm{core}}) \otimes \Lambda(0p)$.

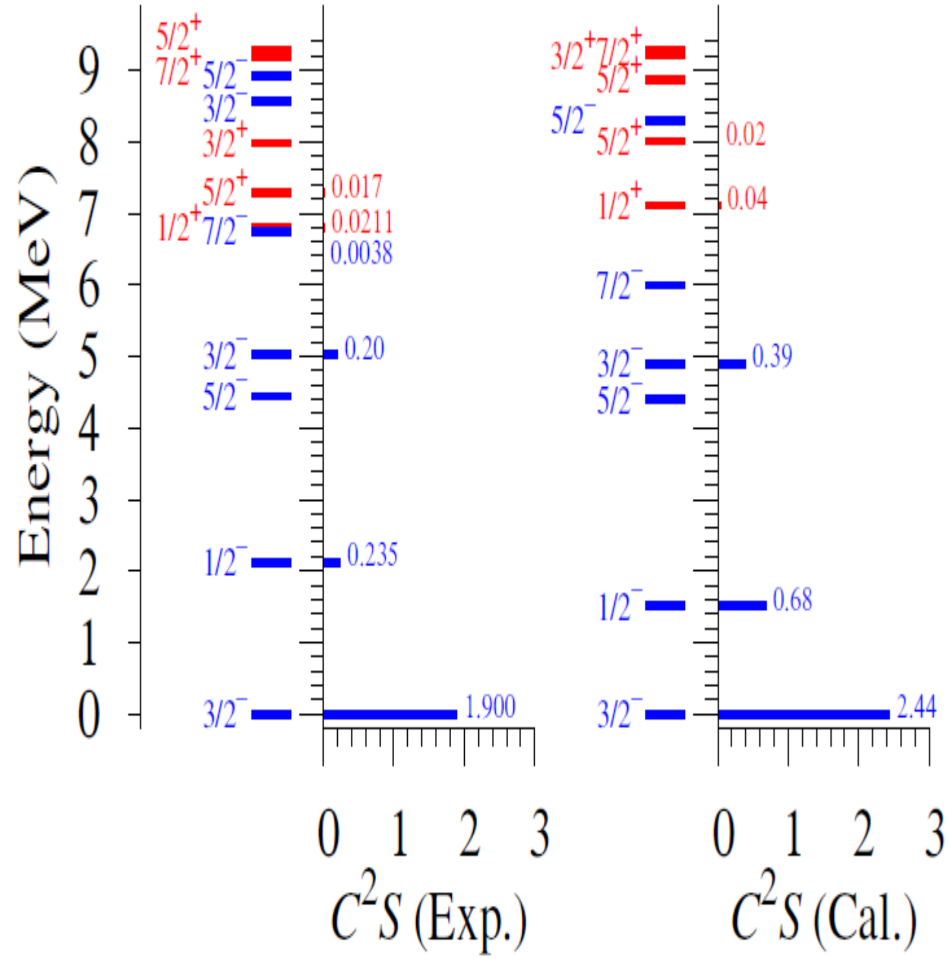
J^+ states (red lines) mainly consist of $^{11}\mathrm{B}(J^+_{\mathrm{core}}) \otimes \Lambda(0s)$.

3. DWIA estimates of (γ,K^+) hypernuclear production cross section



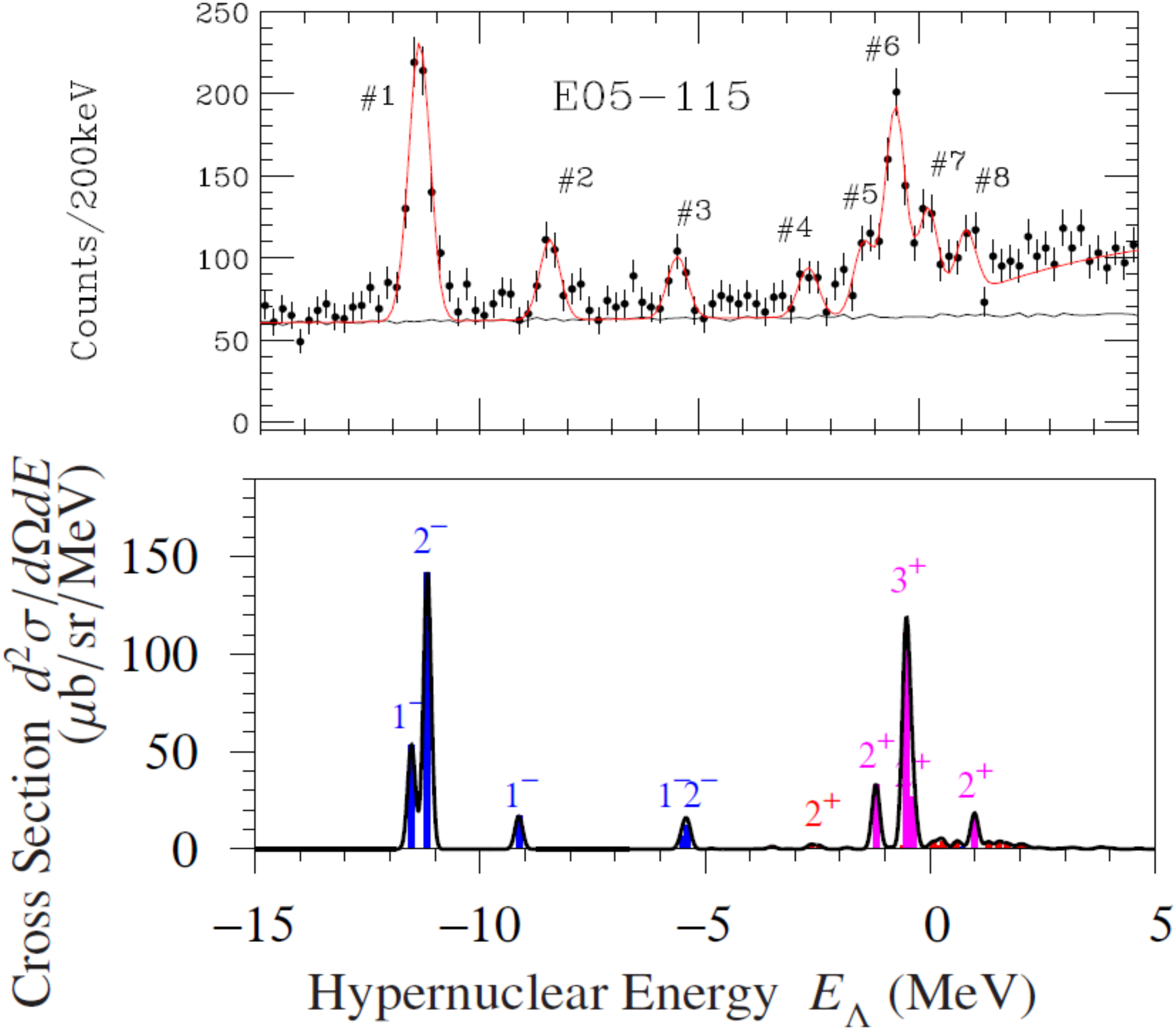
^{11}B

(Energy levels of core nucleus)



Proton pickup S-factor

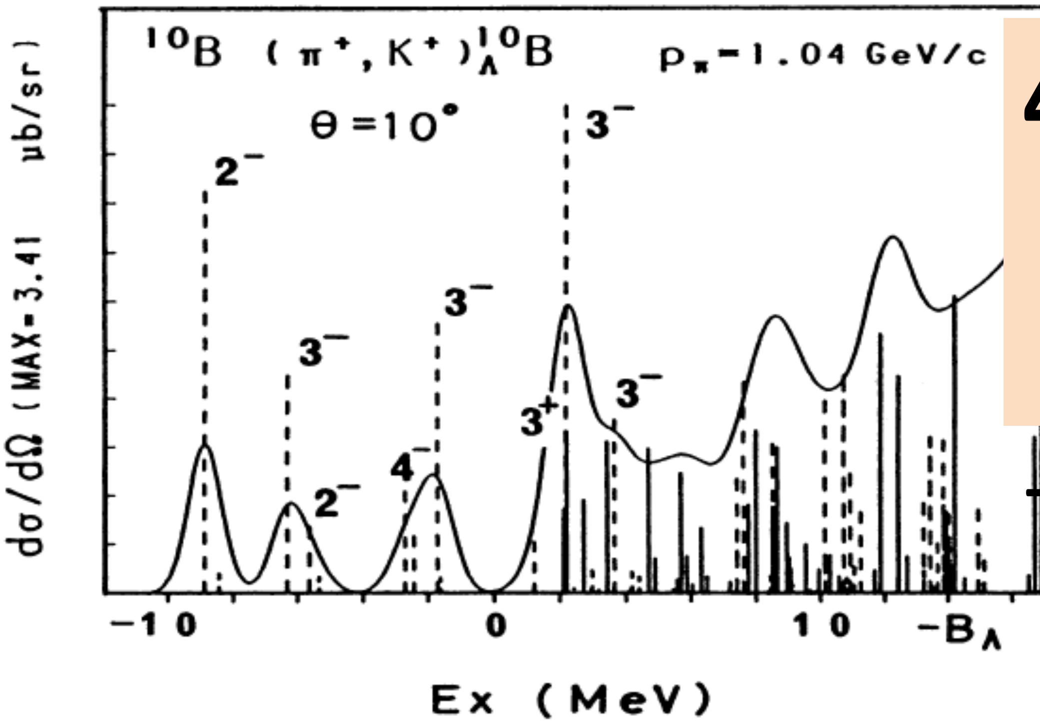
Results : Cross sections of $^{12}C\ (e, e'K^+)\ ^{12}_{\Lambda}B$



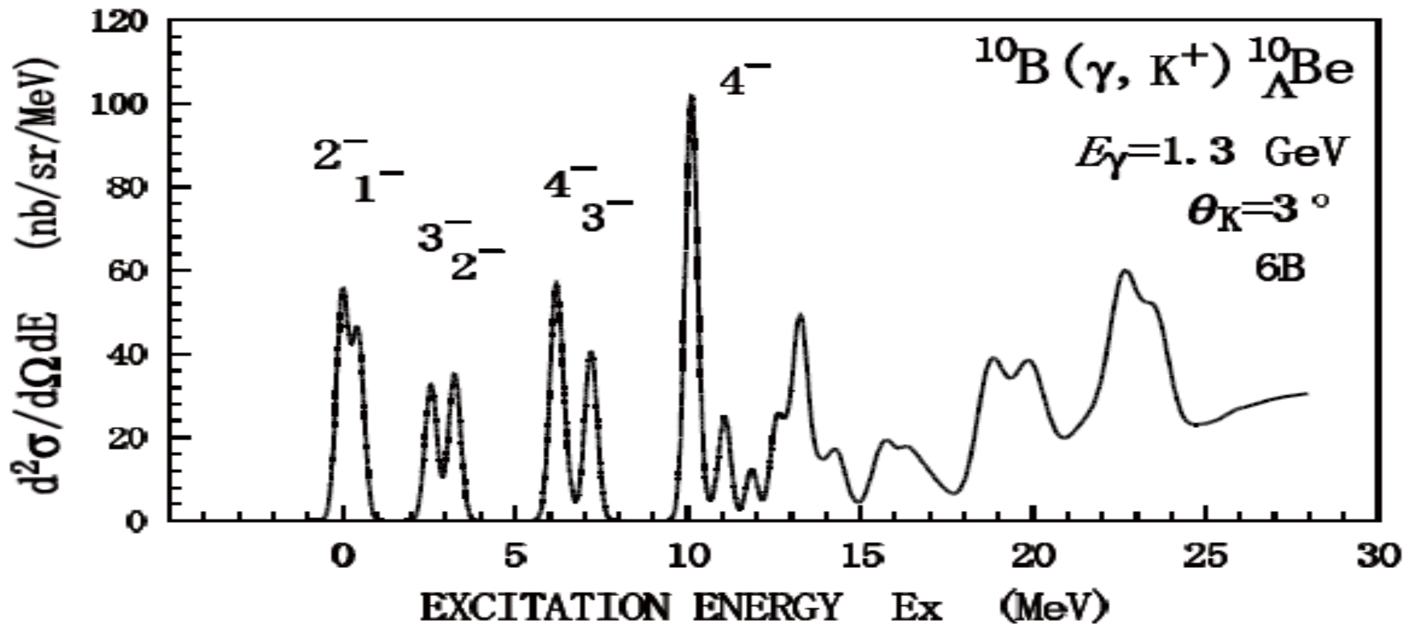
Results : Configuration mixing in the unnatural parity state

$$
\begin{aligned}
{}^{12}_{\Lambda}\mathrm{B}(2^{+}, E_x\!=\!9.056\ \mathrm{MeV}) = {} & 0.84\ [{}^{11}\mathrm{B}(3/2^{+}{}_{1}) \otimes \Lambda(0s)] \\
& + 0.04\ [{}^{11}\mathrm{B}(5/2^{+}{}_{1}) \otimes \Lambda(0s)] \\
& + 0.06\ [{}^{11}\mathrm{B}(5/2^{+}{}_{2}) \otimes \Lambda(0s)] \\
& + 0.02\ [{}^{11}\mathrm{B}(5/2^{+}{}_{3}) \otimes \Lambda(0s)] \\
& + 0.02\ [{}^{11}\mathrm{B}(3/2^{-}{}_{1}) \otimes \Lambda(0p_{3/2})] \\
& + \cdots
\end{aligned}
$$

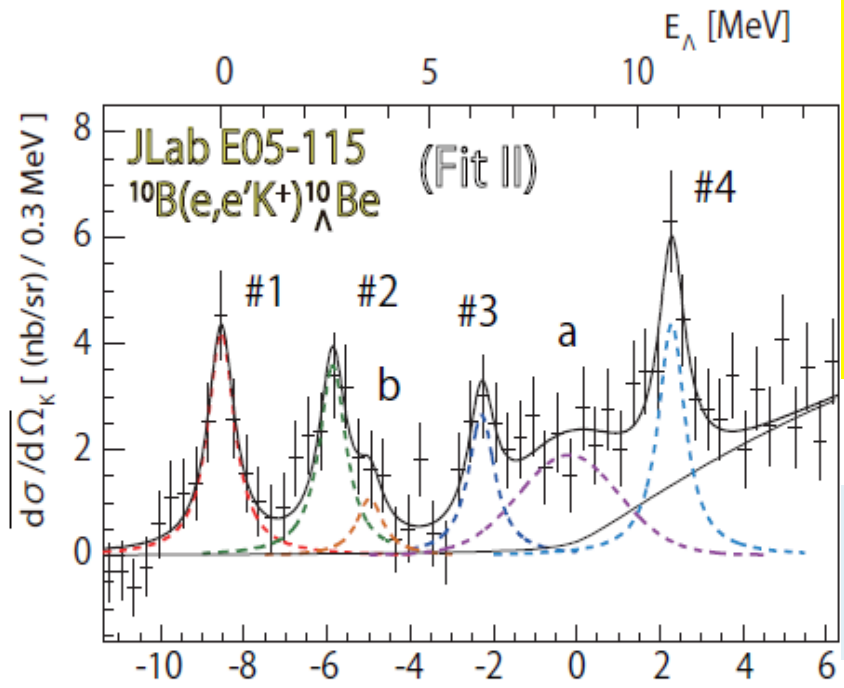
4. Another example
---^{10}B target



$(\pi+,K^+)$ vs. (γ,K^+)

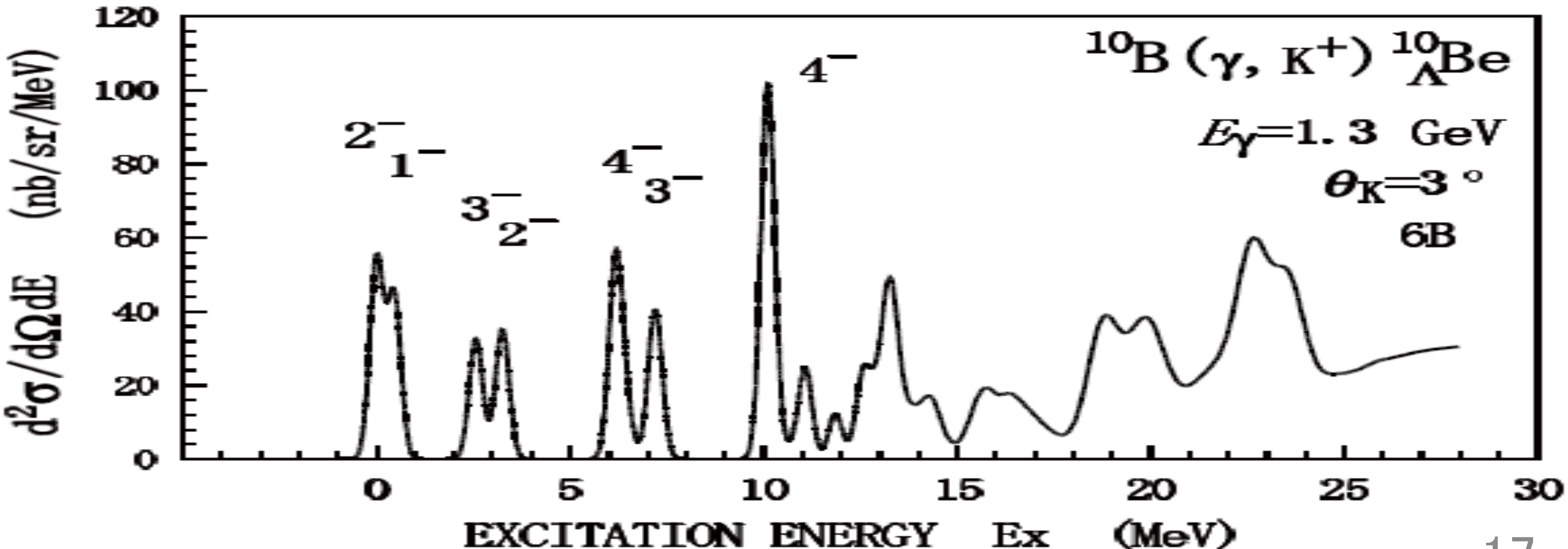


PTP. S.117 (1994)

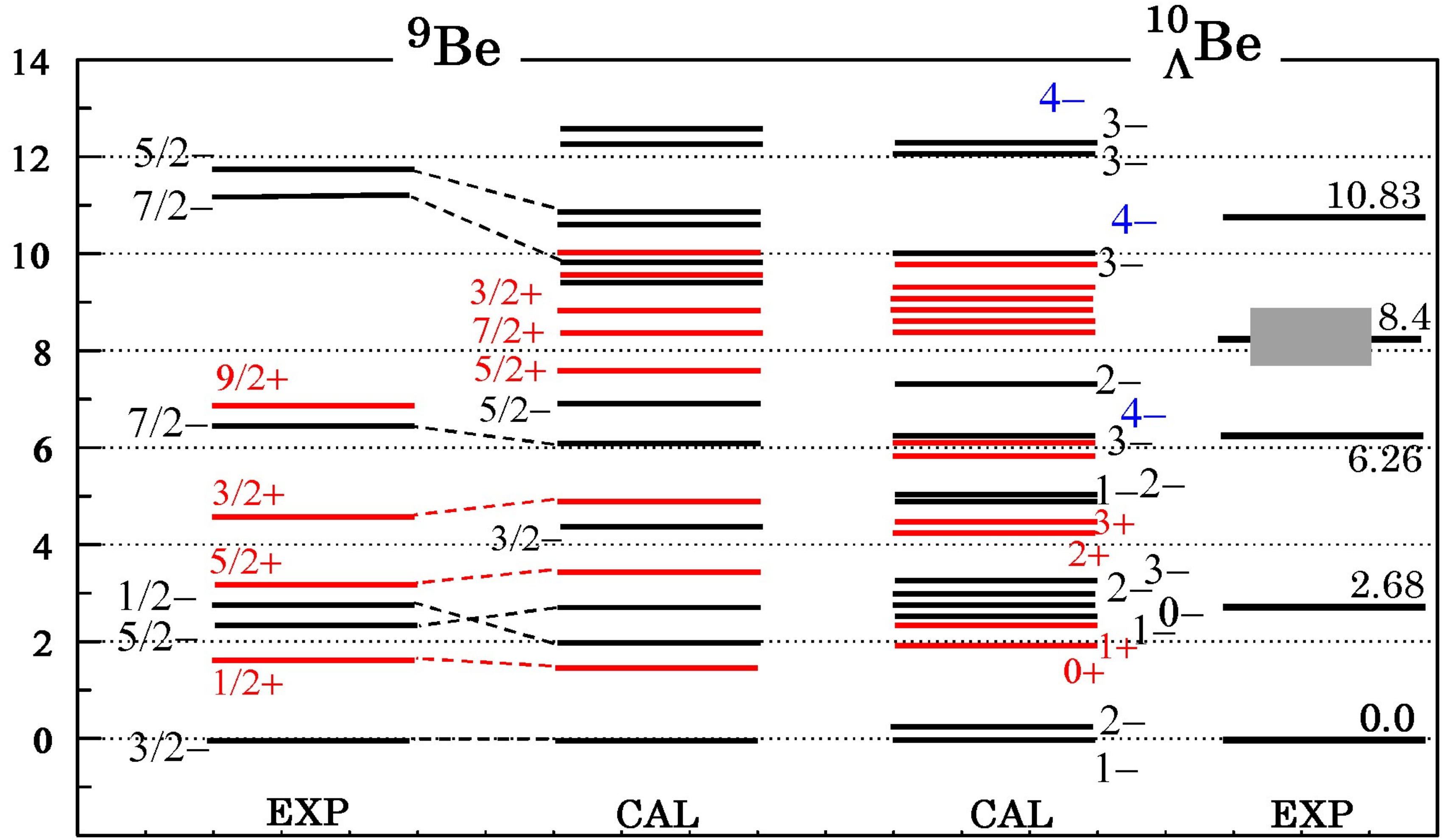


Jlab: ^{10}**B**(e,e'K+)$^{10}{}_{\Lambda}$**Be**
Exp. Published recently,
T. Gogami et al.,
P.R. C 93 (2016)

Predicted XS confirmed, but extra yields (a) unpredicted



Energy levels obtained in the similar parity-mixed multi-configuration calculations



(XS calculation is in progress)

5. Summary

(1) High resolution reaction spectroscopic EXPs (e,e'K+) at Jlab (and Mainz): disclosing new interesting feature of hypernuclear structure such as "parity-mixing mediated by hyperon".

(2) Correspondingly, the multi-configuration calculation of level structure are carried out, showing promising results (yet preliminary).

(3) Thus extended WF are used to estimate DWIA cross sections for (e,e'K+) and (pi+,K+) reactions to be compared with Jlab and KEK.(in progress)

Thank you !

Buckup slides follow:

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

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

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

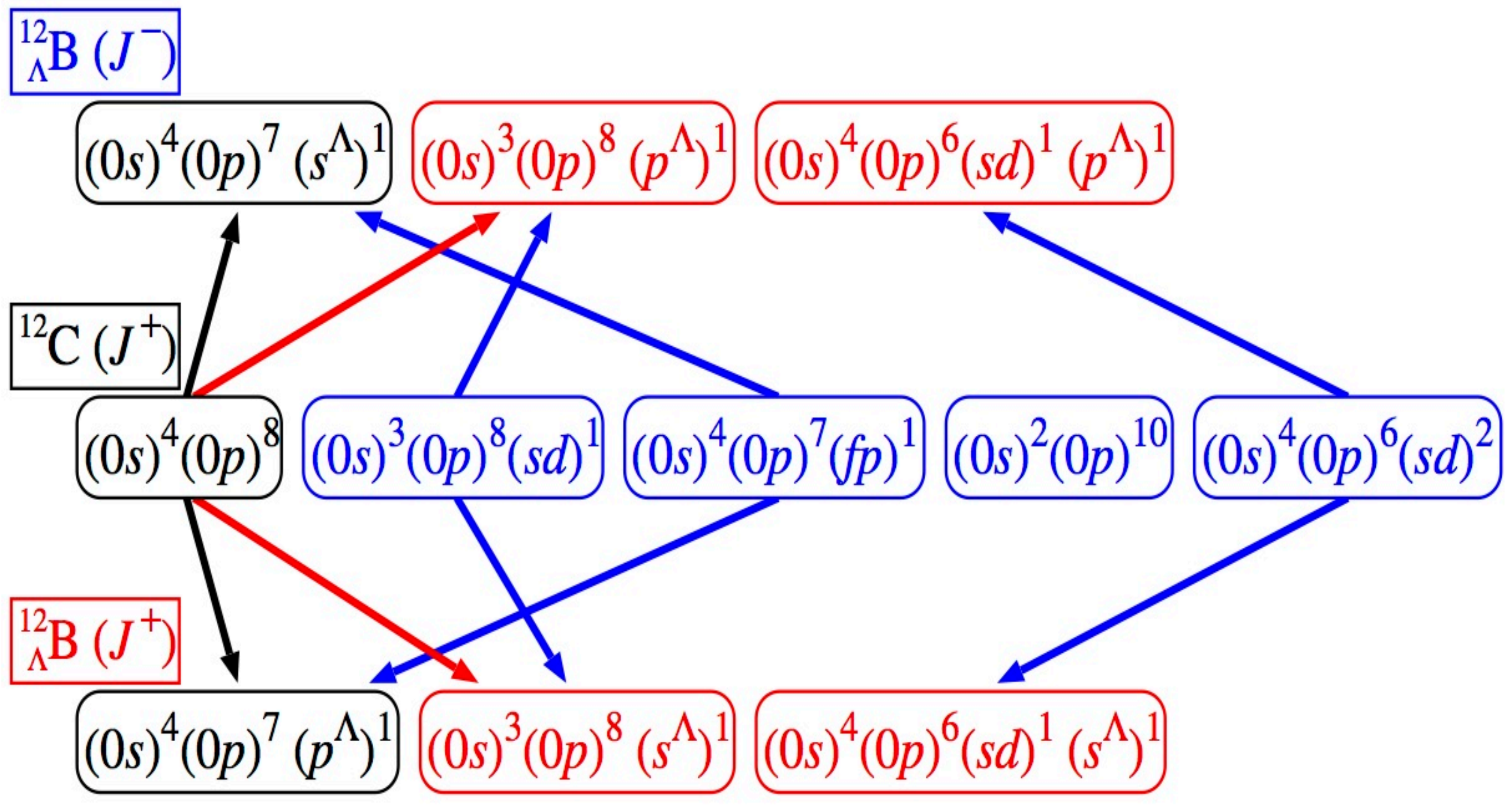
$$^{12}{}_{\Lambda}\mathrm{B}(J_H^-) = \{([s^4]p^7; J_C^-)_0 \times \Lambda_s\}^{(0)} + \{([s^4]p^6(sd)^1; J_C^+)_1 \times \Lambda_p\}^{(2)} + \{([s^3]p^8; J_C^+)_1 \times \Lambda_p\}^{(2)}$$

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

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

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

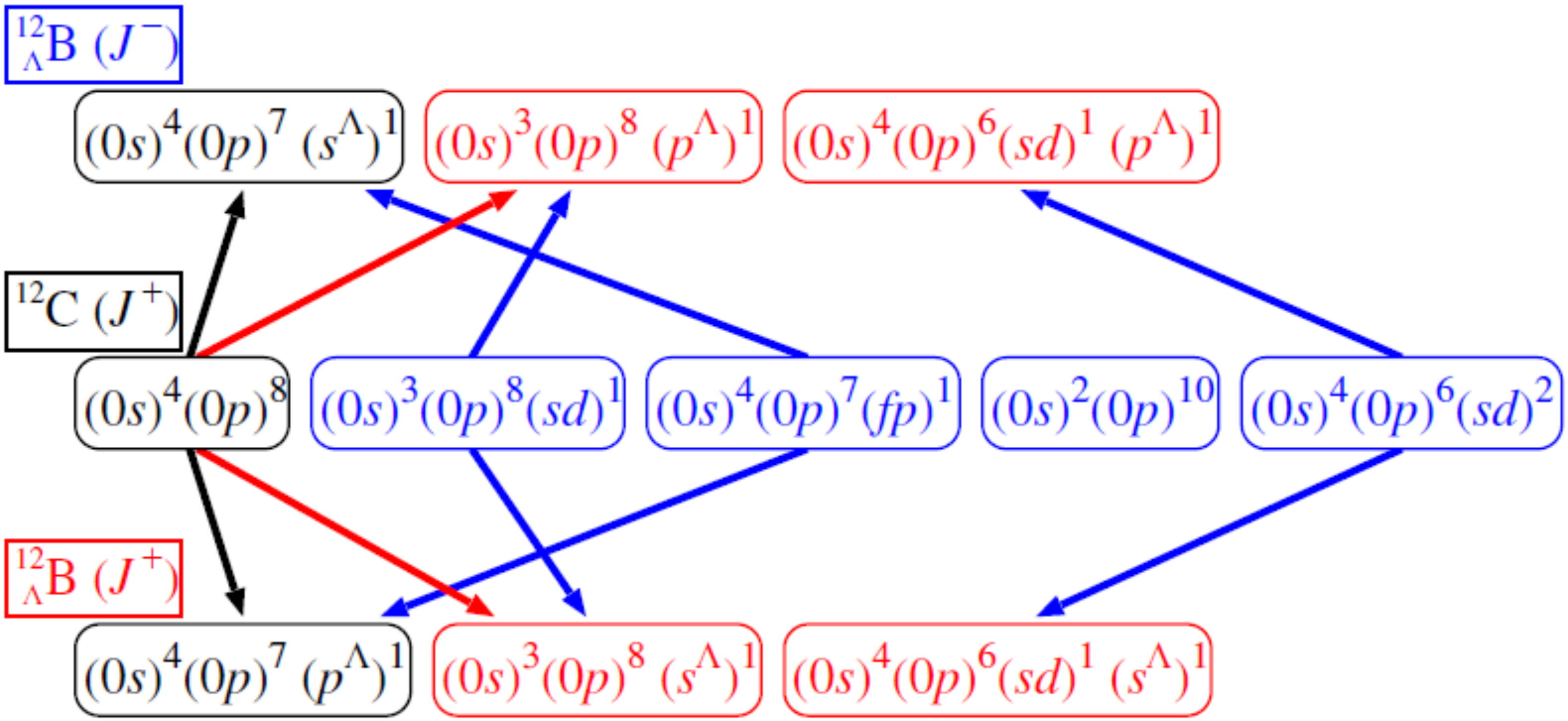
Extended model space for target nucleus



Extension of model space up to 2p-2h (2ħω) for target nucleus ^{12}C allows the $^{12}{}_{\Lambda}$B production through various configurations.

今回の理論研究の試み — 殻殻模空間の拡張 —

コア核が unnatural parity の状態に励起したものを記述できるようにする

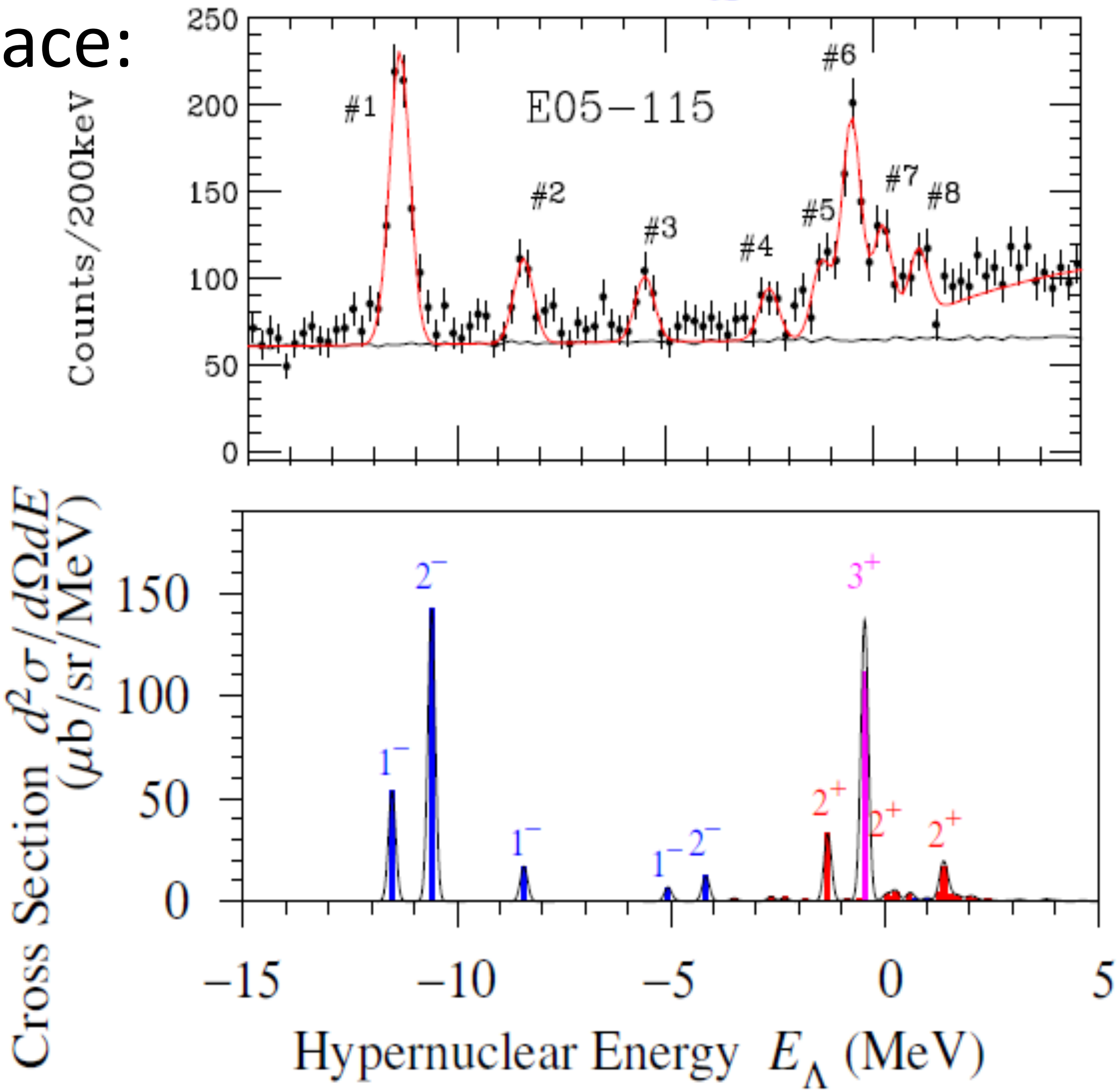


${}^{12}_{\Lambda}\mathrm{B}$ **のコア核は** $1\hbar\omega$ **まで**

標的核 ${}^{12}\mathrm{C}$ **は** $2\hbar\omega$ **まで**

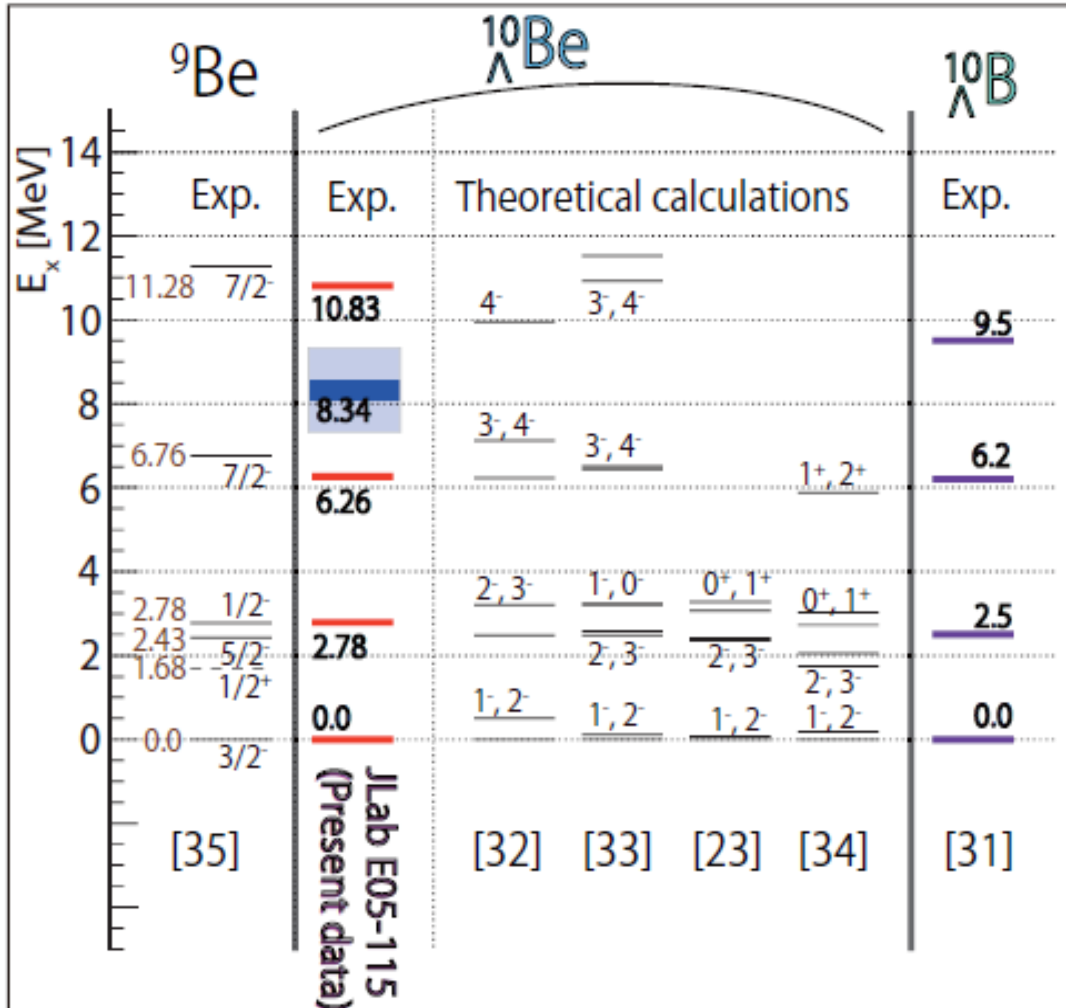
(従来は黒い矢印の遷移のみを扱っていたことになる)

DWIA XS estimates in an extended model space:



Theor. Result is still preliminary, but very promising. Extensive calc. are in progress.

Fit II		
$-B_\Lambda$ [MeV]	E_Λ [MeV]	$\left(\frac{d\sigma}{d\Omega_K}\right)$ [nb/sr]
-8.55±0.07	0.0	17.1±0.5
-5.87±0.18	2.68±0.19	14.5±0.4
-2.29±0.14	6.26±0.15	10.7±0.3
+2.29±0.07	10.83±0.10	17.7±0.5
-0.19±0.38	8.36±0.39	20.5±0.6
-4.98±0.53	3.57±0.53	4.4±0.1



DWIA XS calculations with extended WF are in progress.

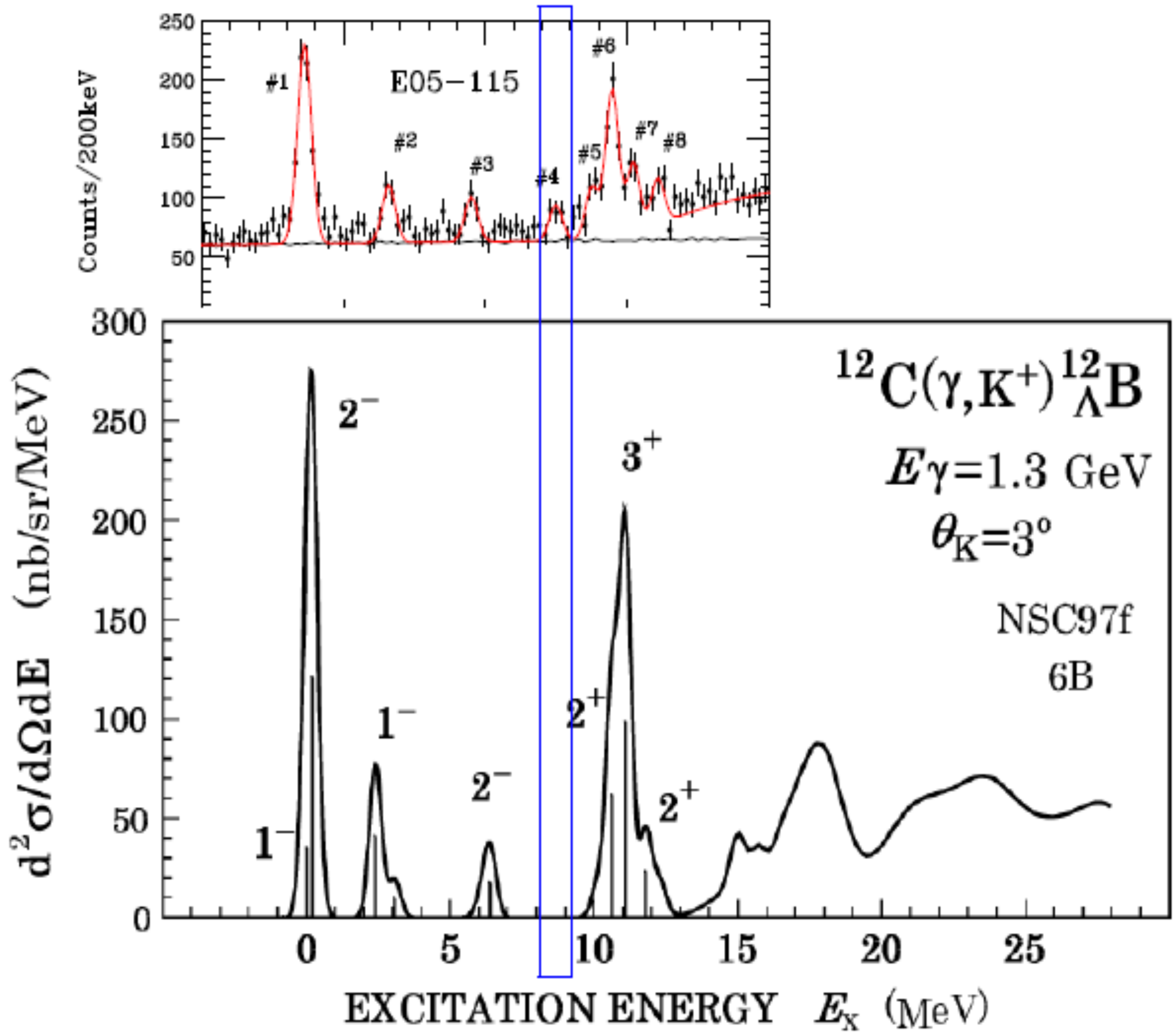
Summary

In order to get a comprehensive description of hypernuclear structure, we have introduced the multi-configuration wave functions in which we take account of the parity-mixing intershell coupling mediated by a Λ-hyperon.

Recent $(e, e'K^+)$ reaction experiments done at the Jefferson Lab have provided us with remarkably high resolution data for p-shell hypernuclei. These experiments have confirmed the major peaks and subpeaks predicted by the DWIA calculations based on the normal-parity nuclear core wave functions coupled with a Λ-hyperon in s- and p-orbits. At the same time, the data also show some extra subpeaks which seem difficult to be explained within the p-shell nuclear normal parity configurations employed so far. Thus we have extended the model space so as to include the new configuration which consists of non-normal parity nuclear core-excited states and the Λ in s-orbit. By this extension, we emphasize that the Λ-hyperon plays an interesting role to induce intershell mixing of the nuclear core-excited states having different parities. This is a challenge in view of the present-day hypernuclear spectroscopic study.

通常の p 殻模型計算との比較

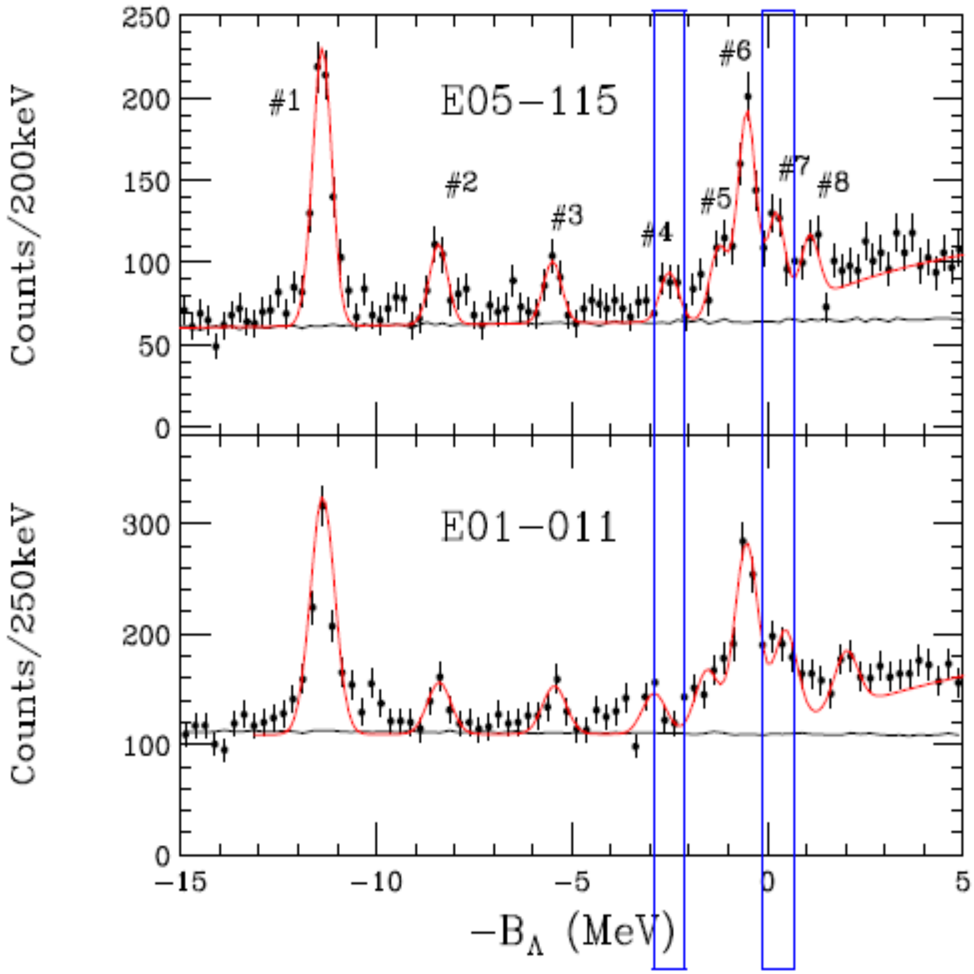
$^{12}C(\gamma, K^+)^{12}_{\Lambda}B$ 生成断面積の理論計算　T. Motoba *et al.*, PTPS185, 224 (2010)



最近の p 殻 Λ ハイパー核の生成実験

$^{12}C(e, e'K^+)$ による $^{12}_{\Lambda}B$ ハイパー核の生成

JLab Hall C E01-011 and E05-115 L. Tang *et al.*, PRC90, 034320 (2014)



殻模型ハミルトニアン

NN 有効相互作用

$\langle p^2 \| V \| p^2 \rangle$	**Cohen-Kurath (8–16) TBME** S. Cohen, D. Kurath, NP73, 1 (1965)
$\langle (sd)^2 \| V \| (sd)^2 \rangle$	**modified Kuo-Brown G-matrix** T. T. S. Kuo, G. E. Brown, NP85, 40 (1966)
$\langle p(sd) \| V \| p(sd) \rangle$	**Millener-Kurath** D. J. Millener, D. Kurath, NPA255, 315 (1975)
$\langle p^2 \| V \| (sd)^2 \rangle$	**modified Kuo-Brown G-matrix (SFO)** T. Suzuki, R. Fujimoto, T. Otsuka, PRC67, 044302 (2003)
それ以外	**Anantaraman-Toki-Bertsch G-matrix** N. Anantaraman, H. Toki, G. F. Bertsch, NPA398, 269 (1983)

ΛN 有効相互作用

$\langle N\Lambda \| V \| N\Lambda \rangle$	**Nijmegen NSC97f** Th. A. Rijken, V. G. J. Stoks, Y. Yamamoto, PRC59, 21 (1999)

核子の 1 粒子エネルギー

Unnatural parity 状態のコア核を現すために sd 殻軌道について調整