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Hypernuclear production spectroscopy with an extended shell model

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collaborated with

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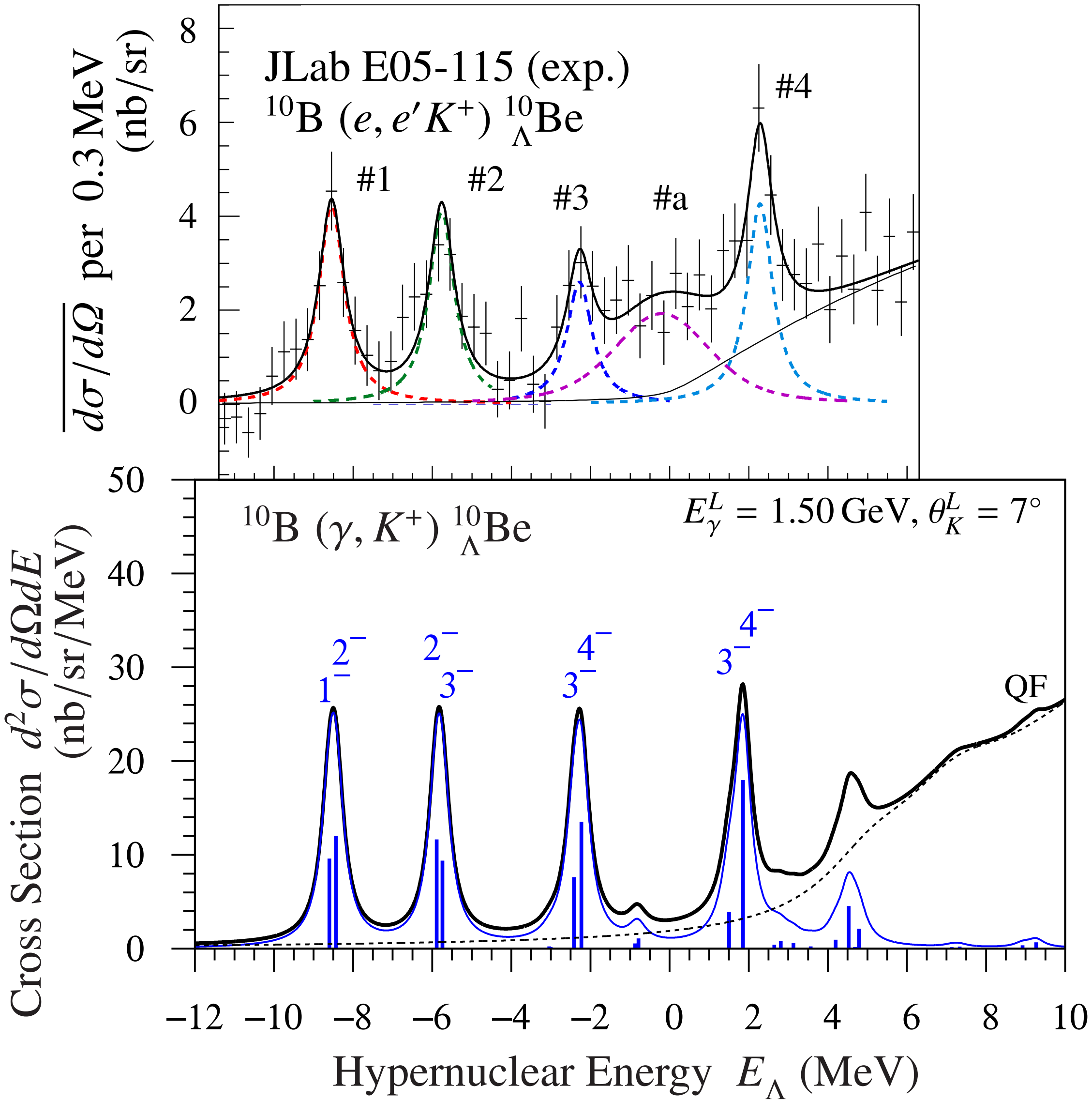
Introduction

- **In production of hypernuclei, $(e, e'K^+)$ reaction experiments with high-resolution have been performed at Jlab.**
- **New projects of (K^-, π^-) and (π^+, K^+) reaction experiments with high-intensity and high-resolusion are being at J-PARC.**
- **Detailed look in Jlab $(e, e'K^+)$ spectroscopic data requires an extended description with multi-configuration parity-mixing mediated by hyperon.**
- **We have extended the model space by introducing the new configuration which includes non-normal parity nuclear core-excited states.**
- **We will show the DWIA cross-sections of (K^-, π^-), (π^+, K^+), and (γ, K^+) reactions.**
- **We focus on the *p*-state Λ hyperon in the *p*-shell Λ hypernuclei.**

Recent $(e, e'K^+)$ reaction experiments done at the Jefferson Lab



Recent experimental result

T. Gogami *et al.*, PRC93, 034314 (2016)

Shell-model prediction

T. Motoba *et al.*, PTPS117, 123 (1994)

- **Core nucleus calculated with conventional *p*-shell model**
- **Λ in *s*-orbit**

This experiment has confirmed the major peaks (#1, #2, #3, #4) predicted in DWIA by emplying the Λ particle in *s*-orbit coupled with the nuclear core states confined within the *p*-shell configuration.

However, it is interesting to observe extra strengths at $E_\Lambda = 0$ MeV excitation (a).

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The extension of the model space is necessary and interesting challenge in view of the present hypernuclear spectroscopy.

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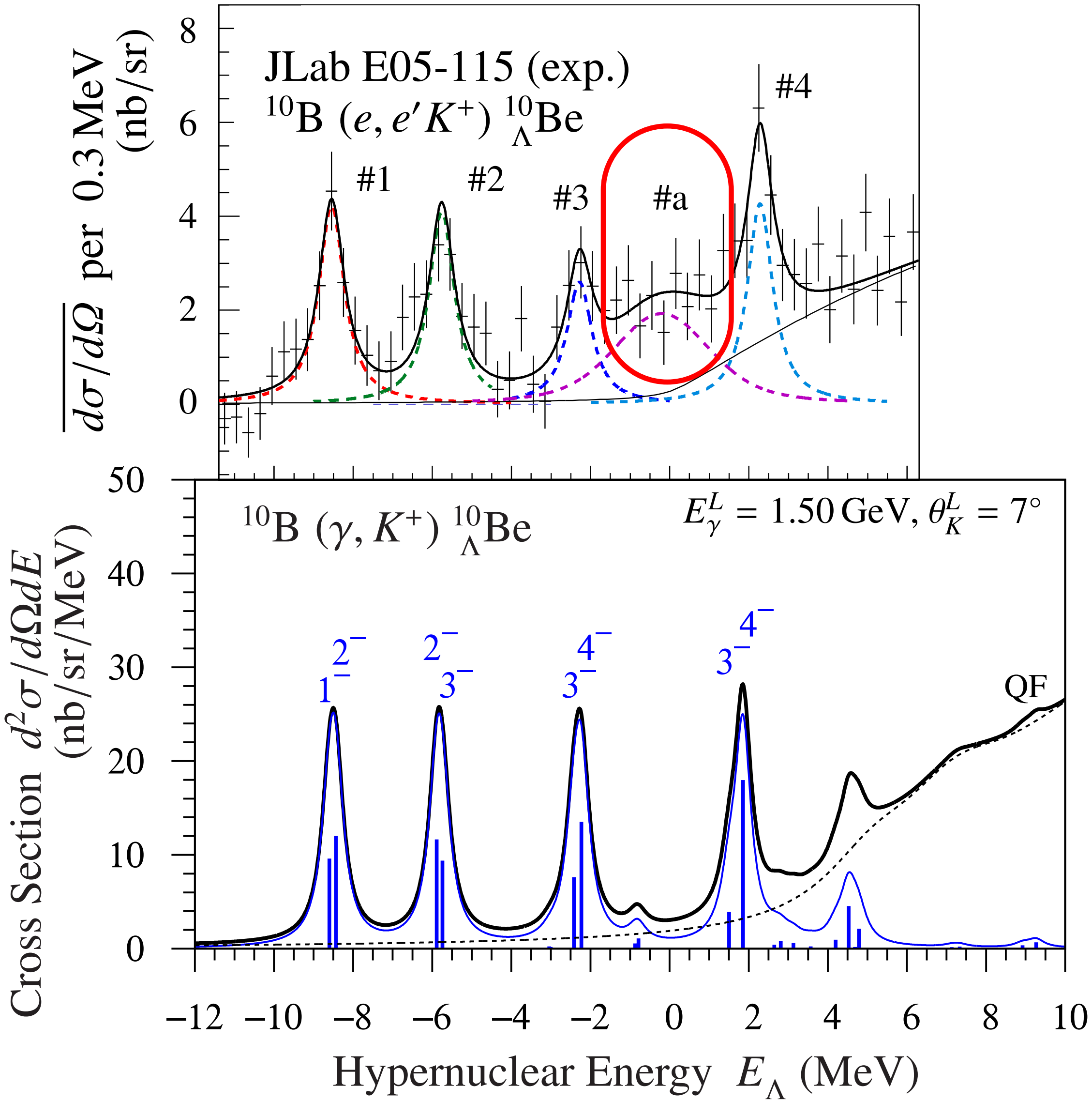

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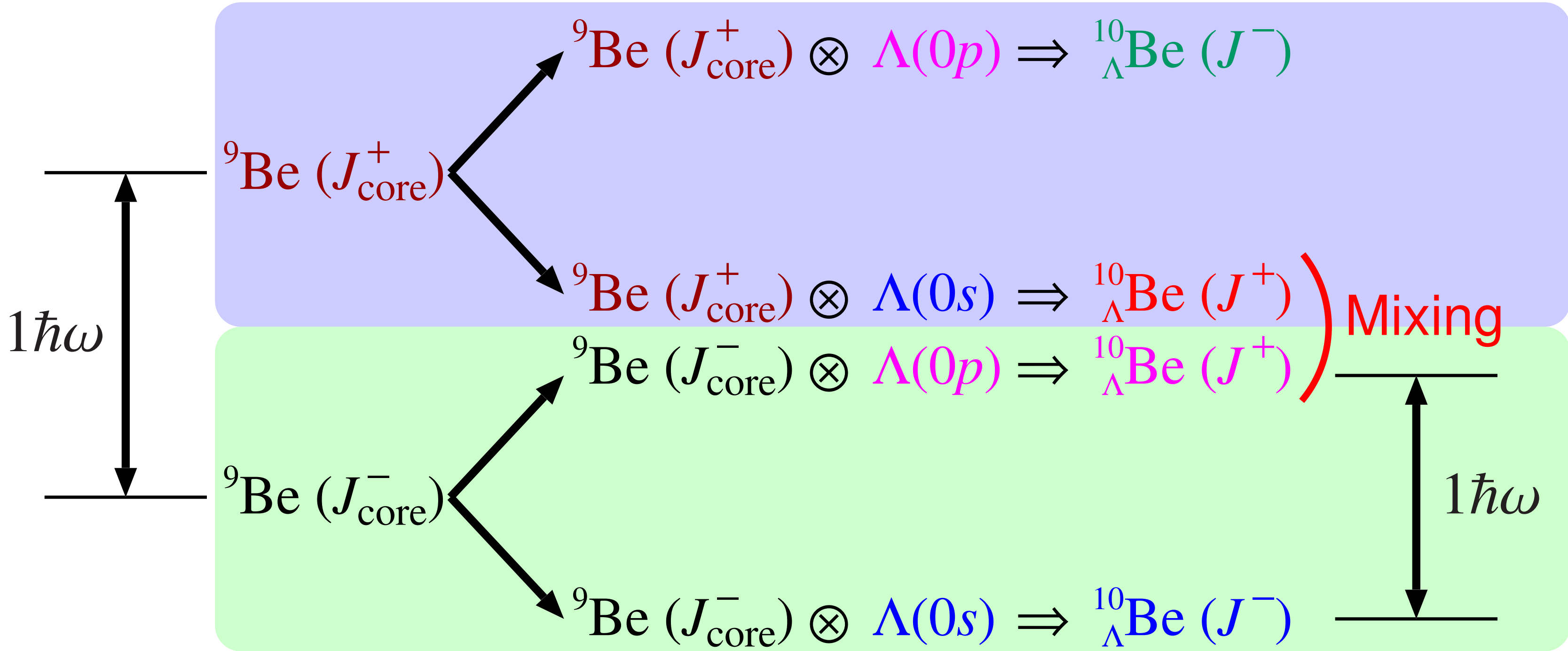
Framework of extended shell model ($^{10}_{\Lambda}$Be case)

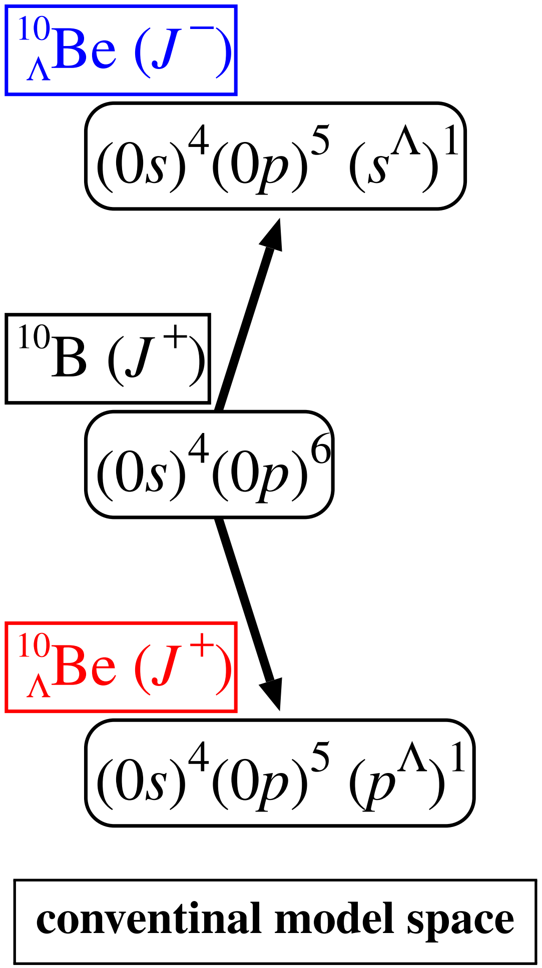


In the conventional shell model, only natural-parity nuclaer-core states (J^-_{core}) are taken into account. Λ particle is in the 0*s* orbit in $^{10}_{\Lambda}$Be(J^-).

In $^{10}_{\Lambda}$Be(J^+), the energy difference between Λ(0*s*) and Λ(0*p*) is 1ħω, and the energy difference between ^{9}Be(J^-_{core}) and ^{9}Be(J^+_{core}) is 1ħω.

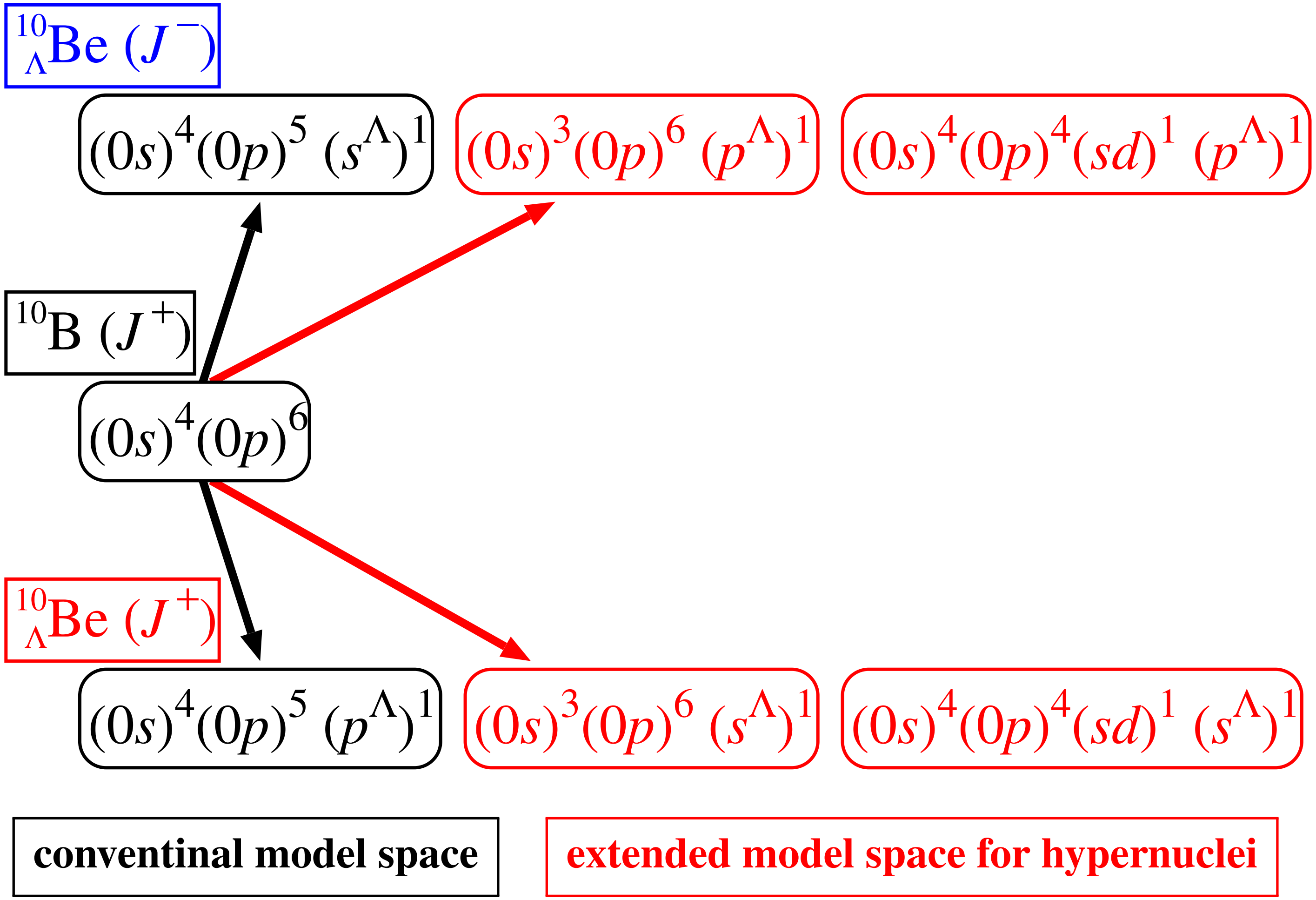
By Λ*N* interaction, natural-parity nuclaer-core configurations and unnatural-parity nuclaer-core configurations can be mixed.

Extended model space for target nucleus ^{10}B



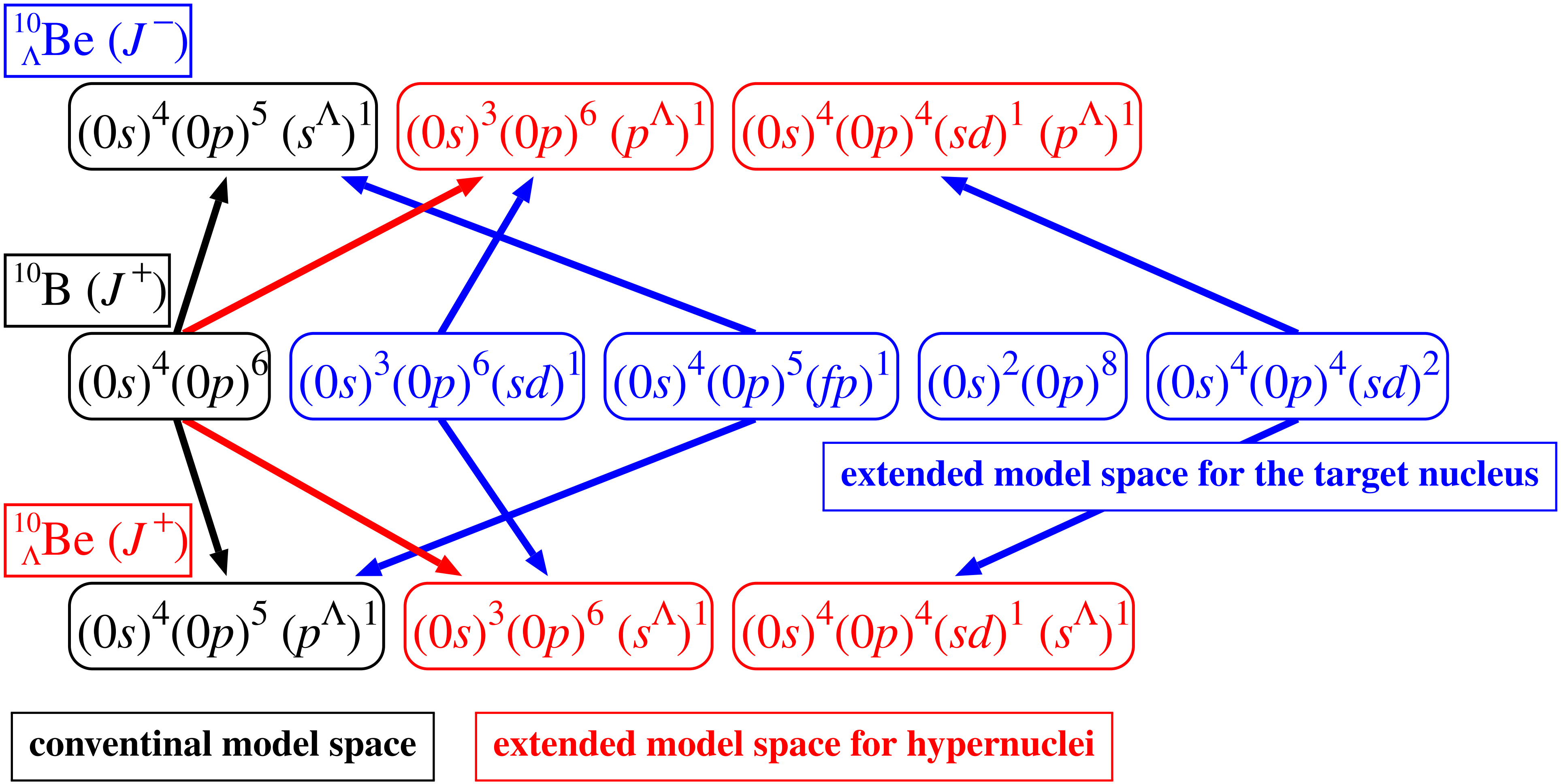
Extension of model space for target nucleus ^{10}B up to 2*p*-2*h* ($2\hbar\omega$) allows the $^{10}_{\Lambda}$Be production through various configurations.

Extended model space for target nucleus ^{10}B



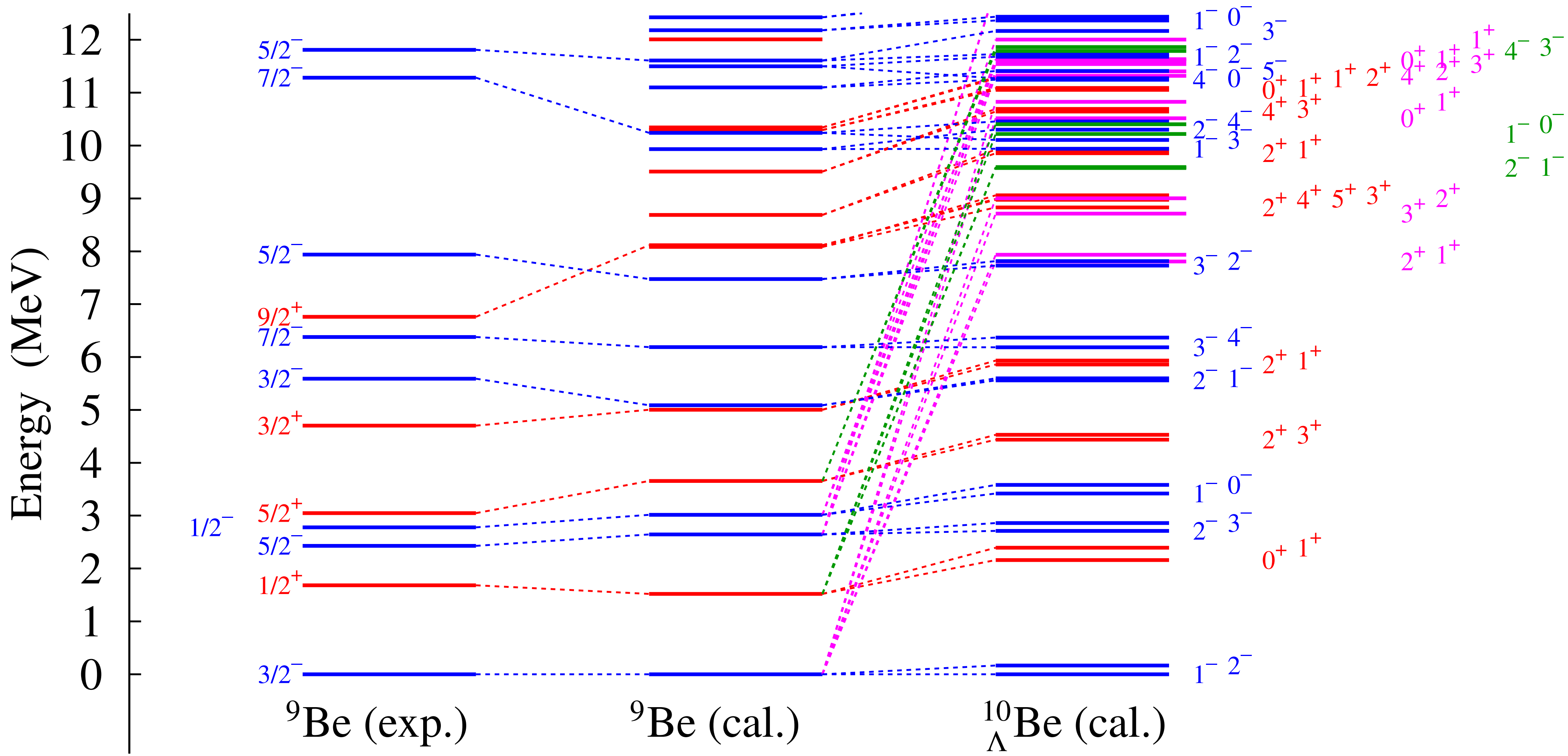
Extension of model space for target nucleus ^{10}B up to $2p$-$2h$ ($2\hbar\omega$) allows the $^{10}_{\Lambda}$Be production through various configurations.

Extended model space for target nucleus ^{10}B



Extension of model space for target nucleus ^{10}B up to $2p$-$2h$ ($2\hbar\omega$) allows the $^{10}_{\Lambda}$Be production through various configurations.

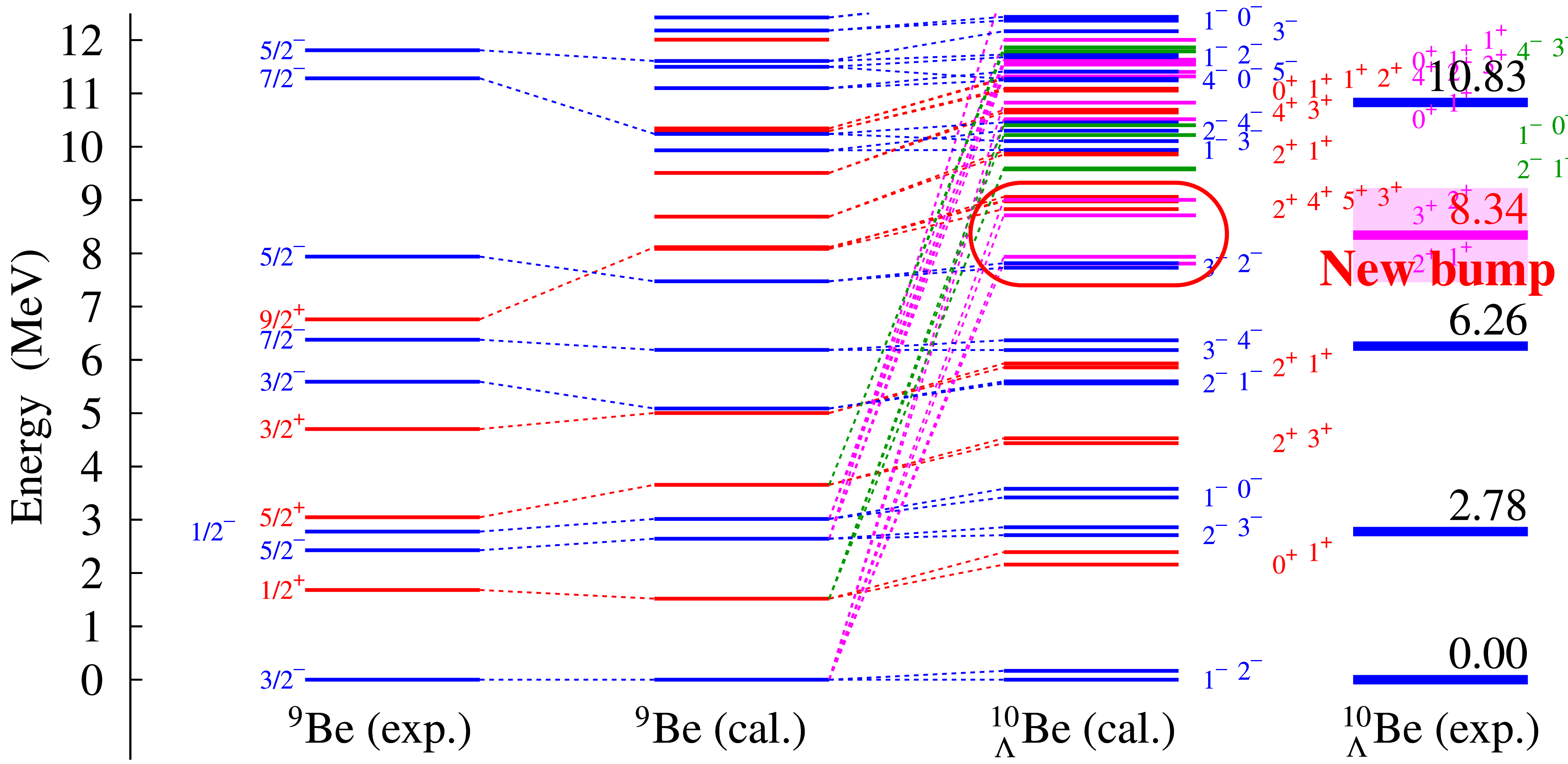
Results : Energy levels of ^{9}Be and $^{10}_{\Lambda}$Be



dominant configurations

blue	J^-; $^9\text{Be}(J^-_{\text{core}}) \otimes \Lambda(0s)$	**green**	J^+; $^9\text{Be}(J^+_{\text{core}}) \otimes \Lambda(0p)$
magenta	J^+; $^9\text{Be}(J^-_{\text{core}}) \otimes \Lambda(0p)$	**red**	J^+; $^9\text{Be}(J^+_{\text{core}}) \otimes \Lambda(0s)$

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



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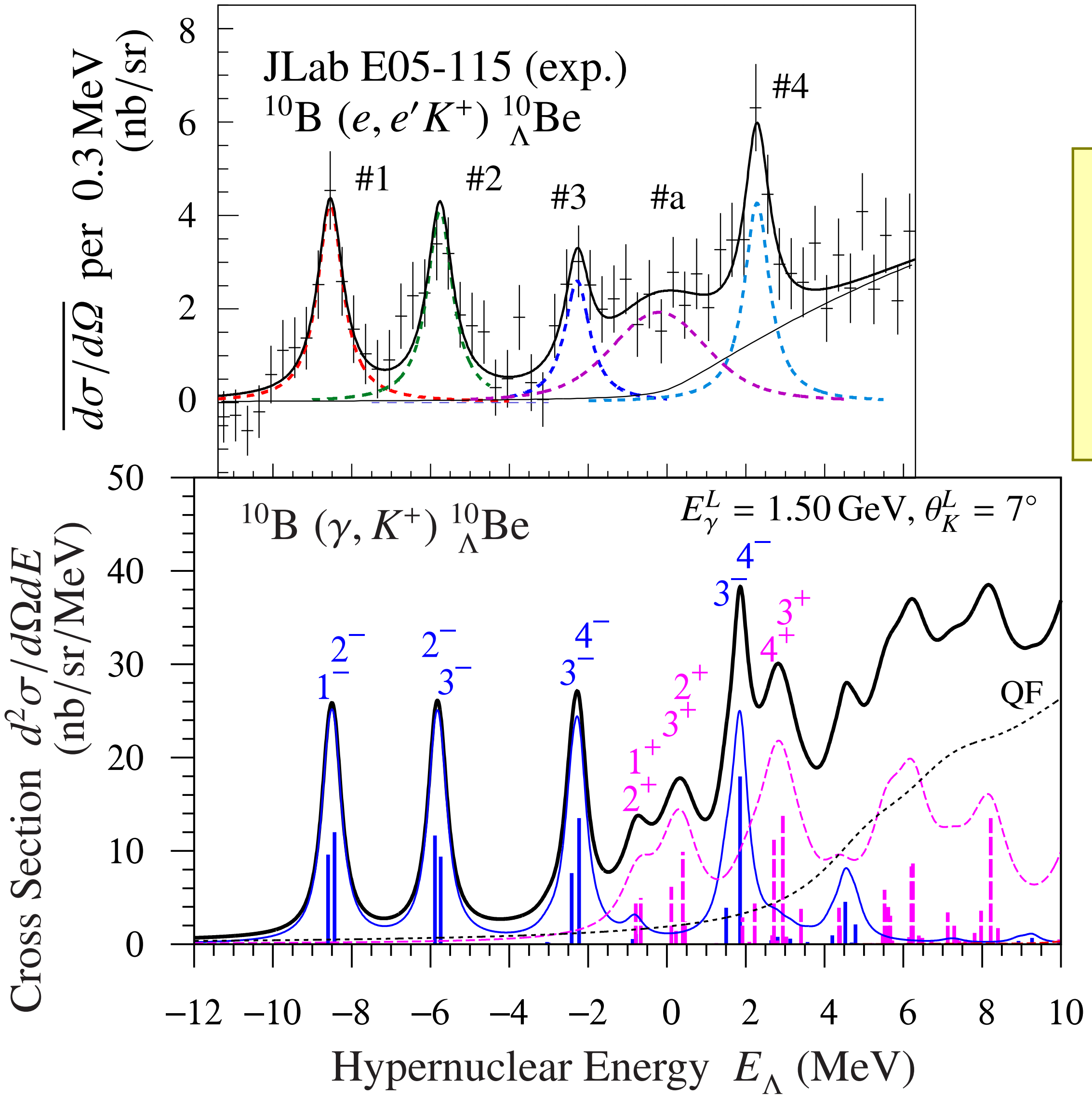
T. Gogami *et al.*, PRC93, 034314 (2016)

Results : Cross sections of the $^{10}\mathrm{B}\ (\gamma, K^+)\ ^{10}_{\Lambda}\mathrm{Be}$ reaction (1)



Recent experimental result
T. Gogami *et al.*, PRC93, 034314 (2016)

For hypernucleus $^{10}_{\Lambda}\mathrm{Be}$
(1) 1*p*-1*h* (1$\hbar\omega$) core excitation
(2) Configration mixing by ΛN int.
are taken into account

DWIA calculation by using Saclay-Lyon model A

Our new calculation reproduces the four major peaks (#1, #2, #3, #4).

Our new calculation explains the new bump (a) as a sum of cross sections of some J^+ states.

Results : Cross sections of the $^{10}\mathrm{B}\,(\gamma, K^+)\,^{10}_{\Lambda}\mathrm{Be}$ reaction (2)

E_γ = 1.5 GeV
θ = 7 deg

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

^{9}Be (J_i)

J_i	E_i (exp)	E_i (cal)
	C2S	C2S
$3/2^-$	0.000	0.000
	1.0(rel)	1.0(rel)
$5/2^-$	2.429	2.644
	0.958	1.020
$7/2^-$	6.380	6.189
	0.668	0.942
$7/2^-$	11.283	10.241
	1.299	1.355

$_{\Lambda}^{10}$Be (J_k) CAL

J_k	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]	
1^-	0.000	−8.600	9.609	**21.62**
2^-	0.165	−8.435	12.008	
2^-	2.712	−5.888	11.654	**21.05**
3^-	2.860	−5.740	9.391	
3^-	6.183	−2.417	7.625	**21.13**
4^-	6.370	−2.230	13.505	
$2^+(3)$	7.807	−0.793	4.495	**9.46**
$1^+(3)$	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	
3^-	10.105	1.505	3.913	**21.90**
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	

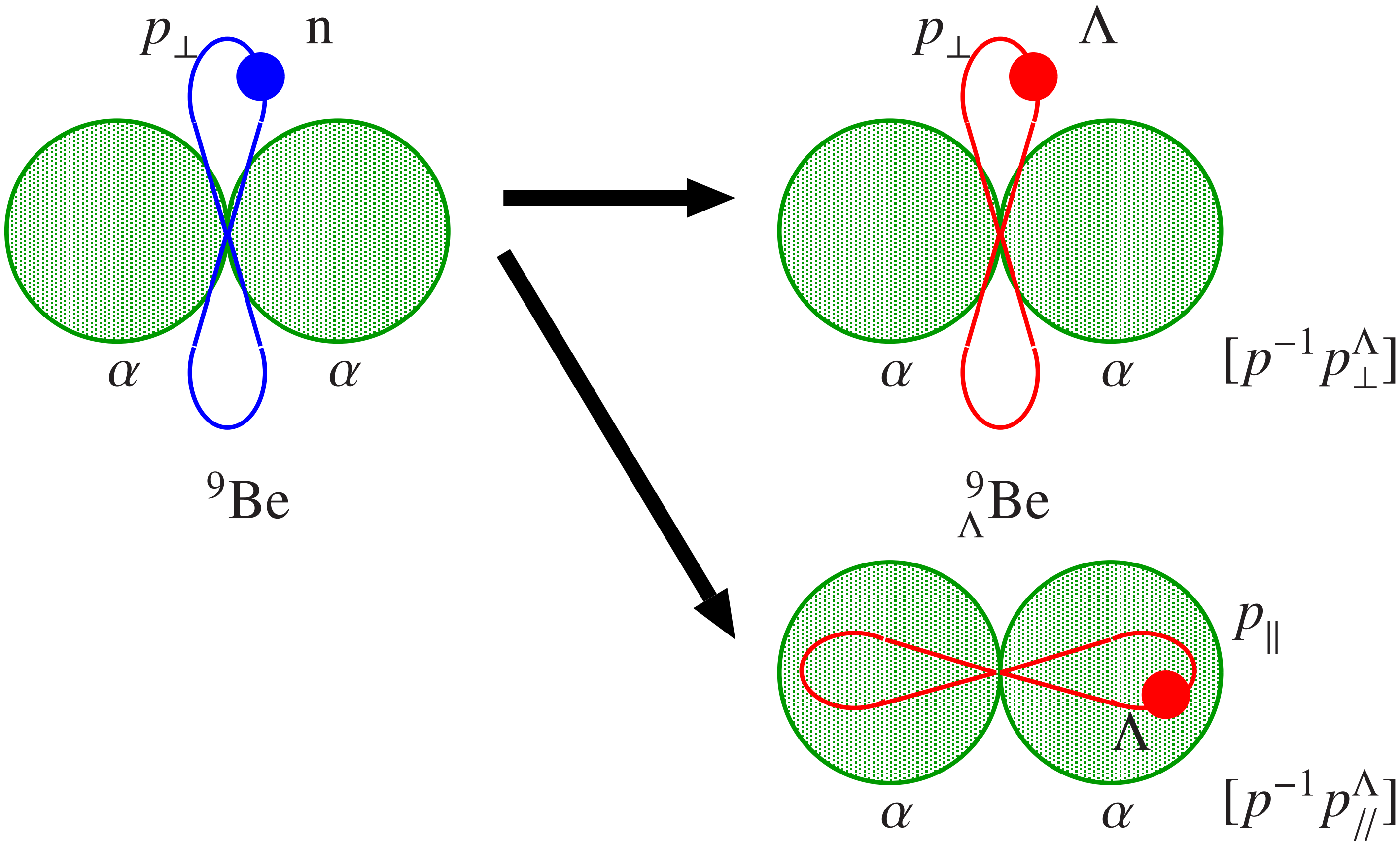
EXP / **Fit I**

exp peak	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]
#1	0.00	−8.55±0.07	**17.0±0.5**
#2	2.78±0.11	−5.76±0.09	**16.5±0.5**
#3	6.26±0.16	−2.28±0.14	**10.5±0.3**
#a	8.34±0.41	−0.20±0.40	**23.2±0.7**
#4	10.83±0.10	2.28±0.07	**17.2±0.5**

Results : Configrations of J^+ states corresponding to the new bump

$J^\pi_n(-B_\Lambda[\mathrm{MeV}])$ 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%

$[p^{-1}p^{\Lambda}_{\perp}]$ and $[p^{-1}p^{\Lambda}_{//}]$ states of $^{9}_{\Lambda}$Be

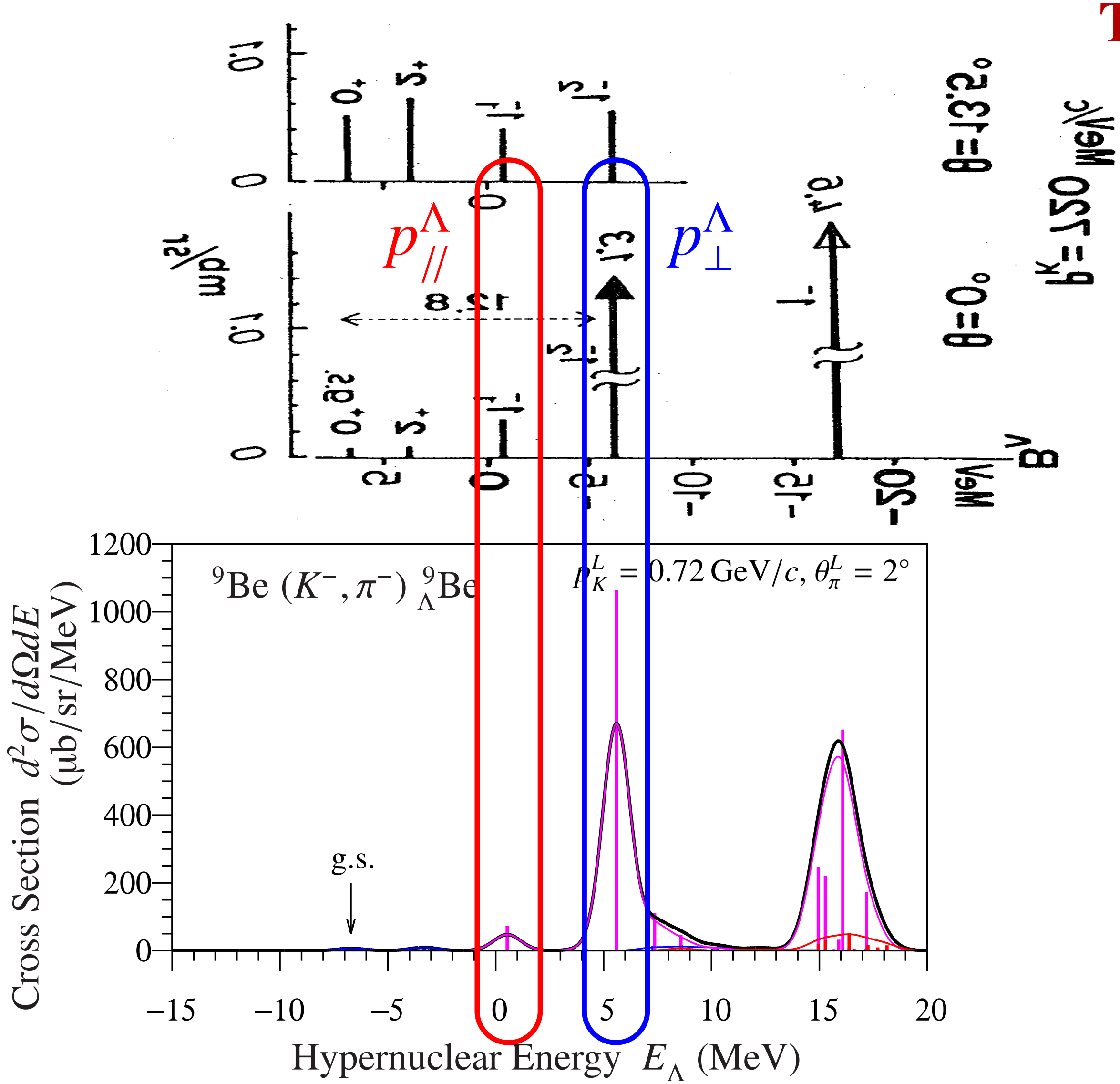


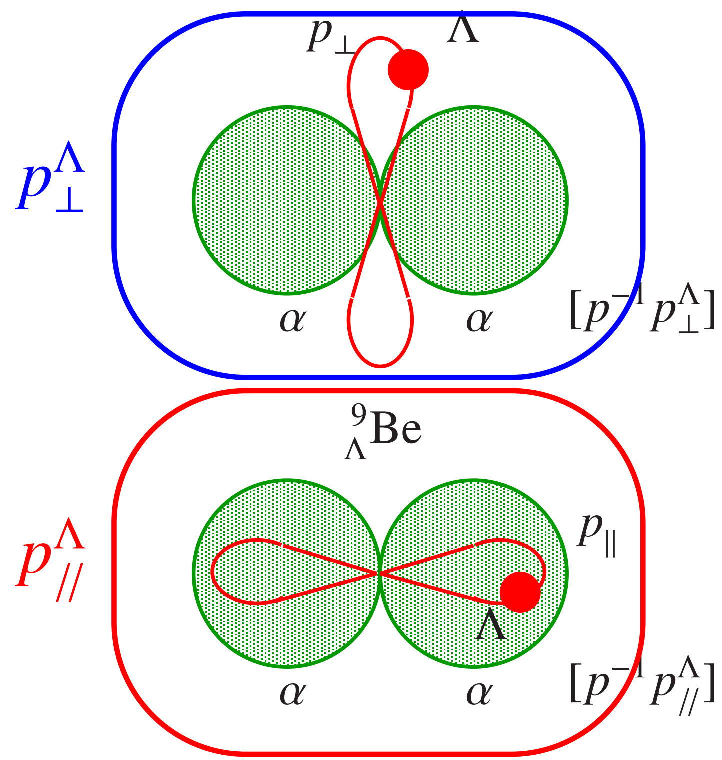
In $^{9}_{\Lambda}$Be, it is well known that the p_{Λ}-state splits into two orbital states expressed by $p_{\perp}$ and $p_{//}$, which is due to the strong coupling with nuclear core deformation having the α-α structure.

T. Motoba *et al.*, PTPS81, 42 (1985)
R. H. Dalitz, A. Gal, PRL36, 362 (1976); AP131, 314 (1981)

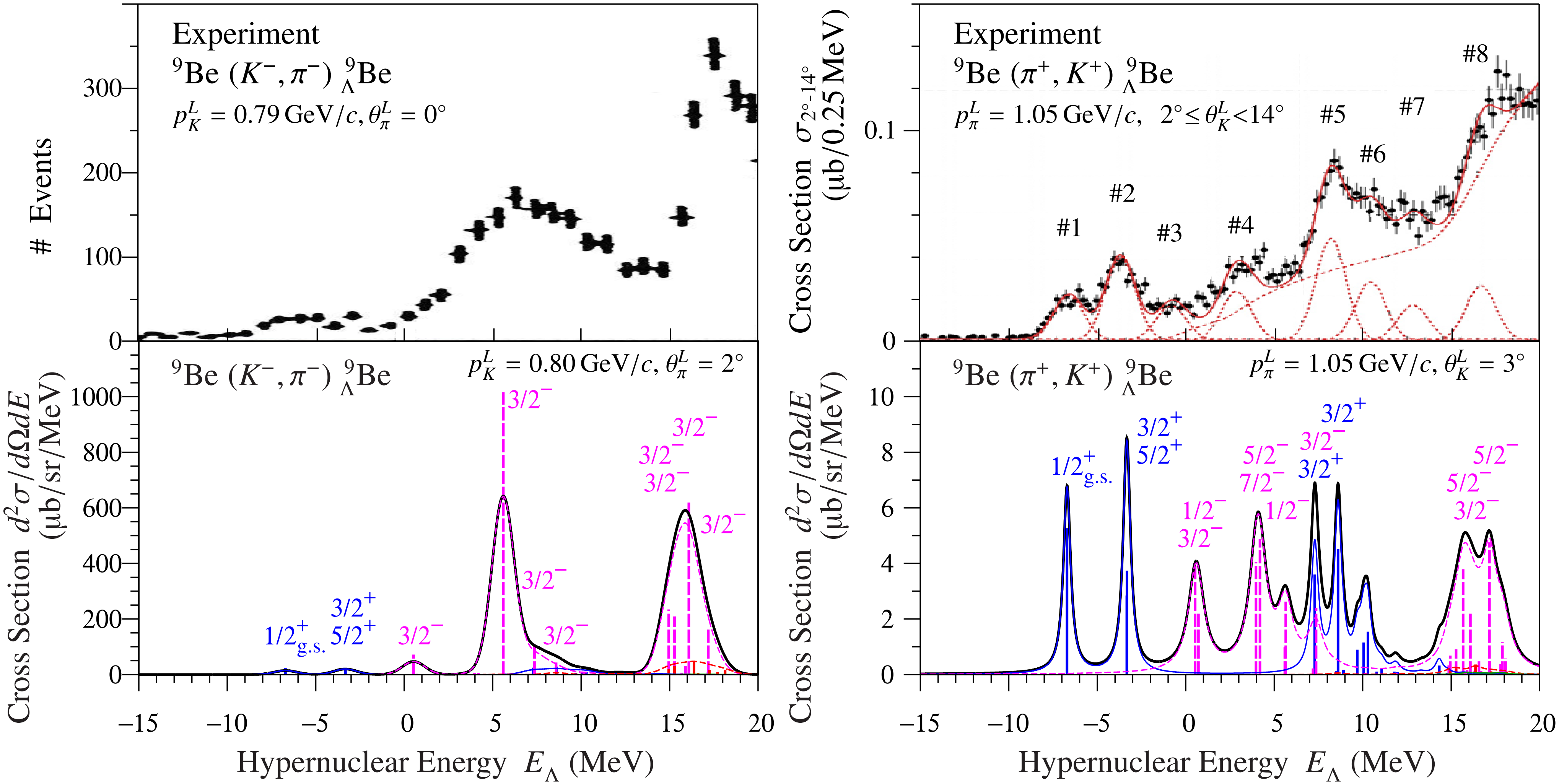
Results : Comparison to the cluster model – Cross section –

T. Motoba *et al.*, PTPS81, 42 (1985)





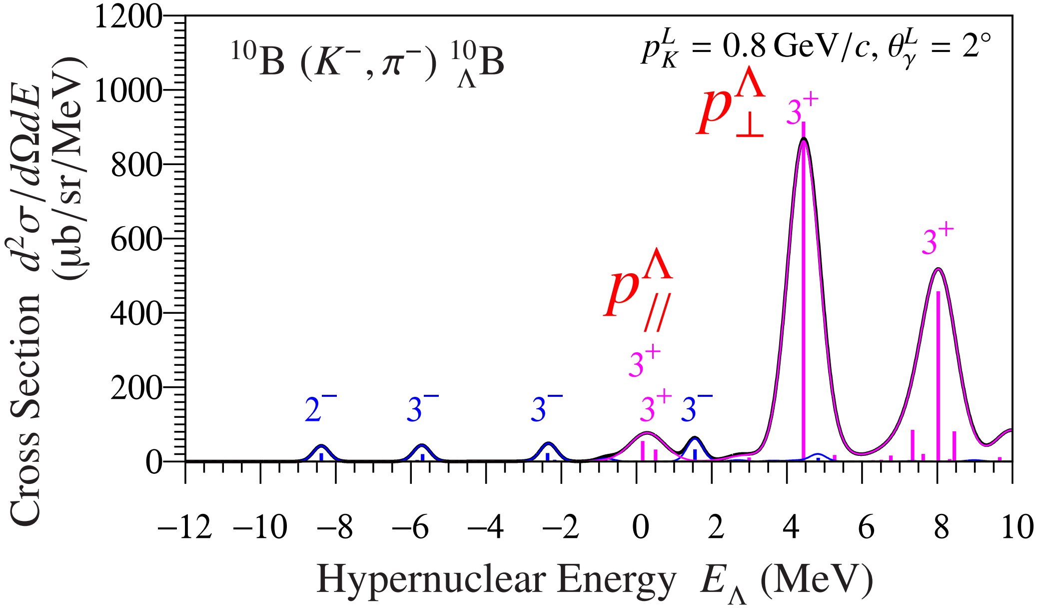
Results : Cross sections of ^{9}Be (K^-, π^-) and ^{9}Be (π^+, K^+) reactions

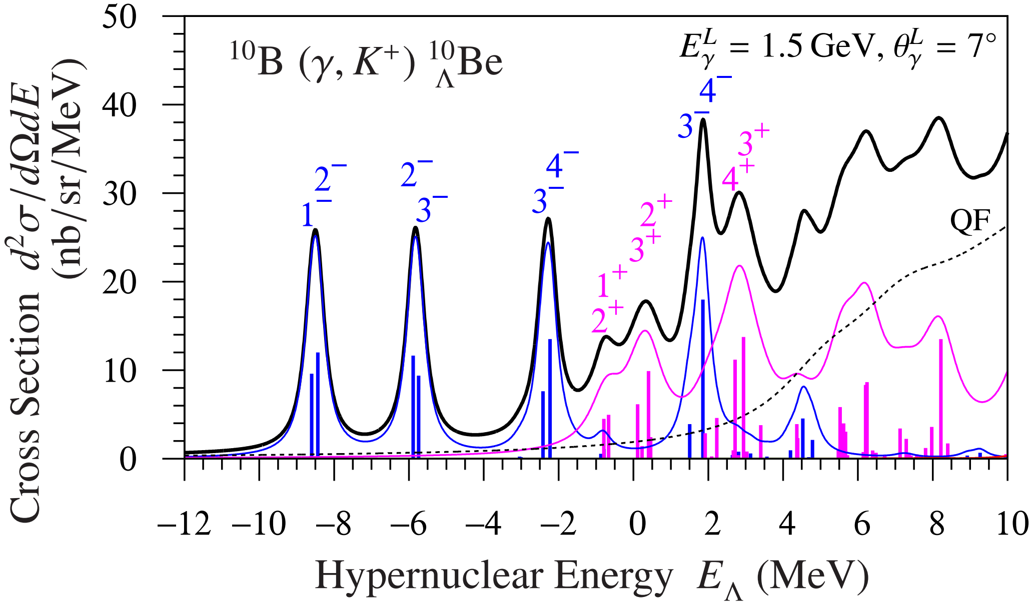


Exp. from **R. Bertini *et al.*, NPA368, 365 (1981)**

Exp. from **O. Hashimoto and H. Tamura, PPNP57, 564 (2006)**

Results : Cross sections of the $^{10}\mathrm{B}\,(K^-,\pi^-)\,^{10}_{\Lambda}\mathrm{B}$ reaction (1)





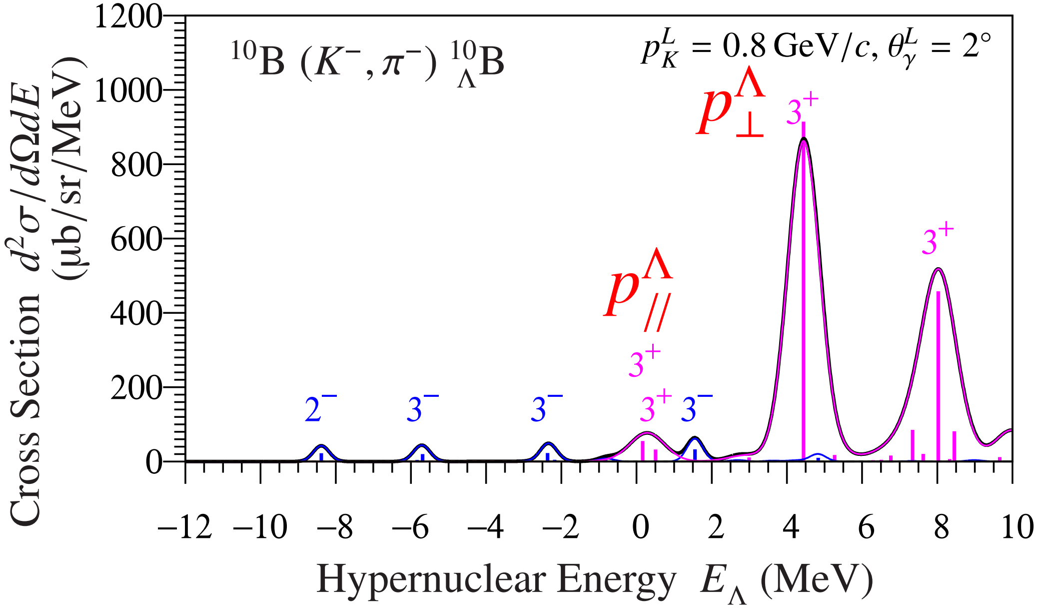
In the (K^-,π^-) reaction, the large peak at $E_\Lambda = 4.4$ MeV is a p-substitutional state via the $p^N_{3/2} \to p^\Lambda_{3/2}$, which is strongly excited by recoilless reaction.

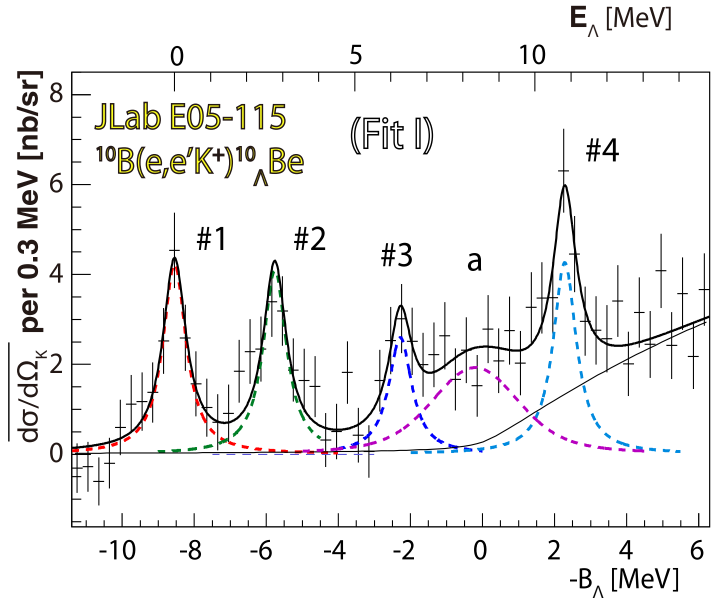
The small peak at $E_\Lambda = 0$ MeV corresponds to the new bump and is explained as a mixture of s^Λ and p^Λ states.

The large peak at $E_\Lambda = 4.4$ MeV in $^{10}_{\Lambda}\mathrm{Be}$ corresponds to the $[p^{-1}p^\Lambda_\perp]$ state in $^{9}_{\Lambda}\mathrm{Be}$ ($^9\mathrm{Be}$ analog state).

The small peak at $E_\Lambda = 0$ MeV in $^{10}_{\Lambda}\mathrm{Be}$ corresponds to the $[p^{-1}p^\Lambda_{//}]$ state in $^{9}_{\Lambda}\mathrm{Be}$.

Results : Cross sections of the $^{10}\mathrm{B}\,(K^-,\pi^-)\,^{10}_{\Lambda}\mathrm{B}$ reaction (2)





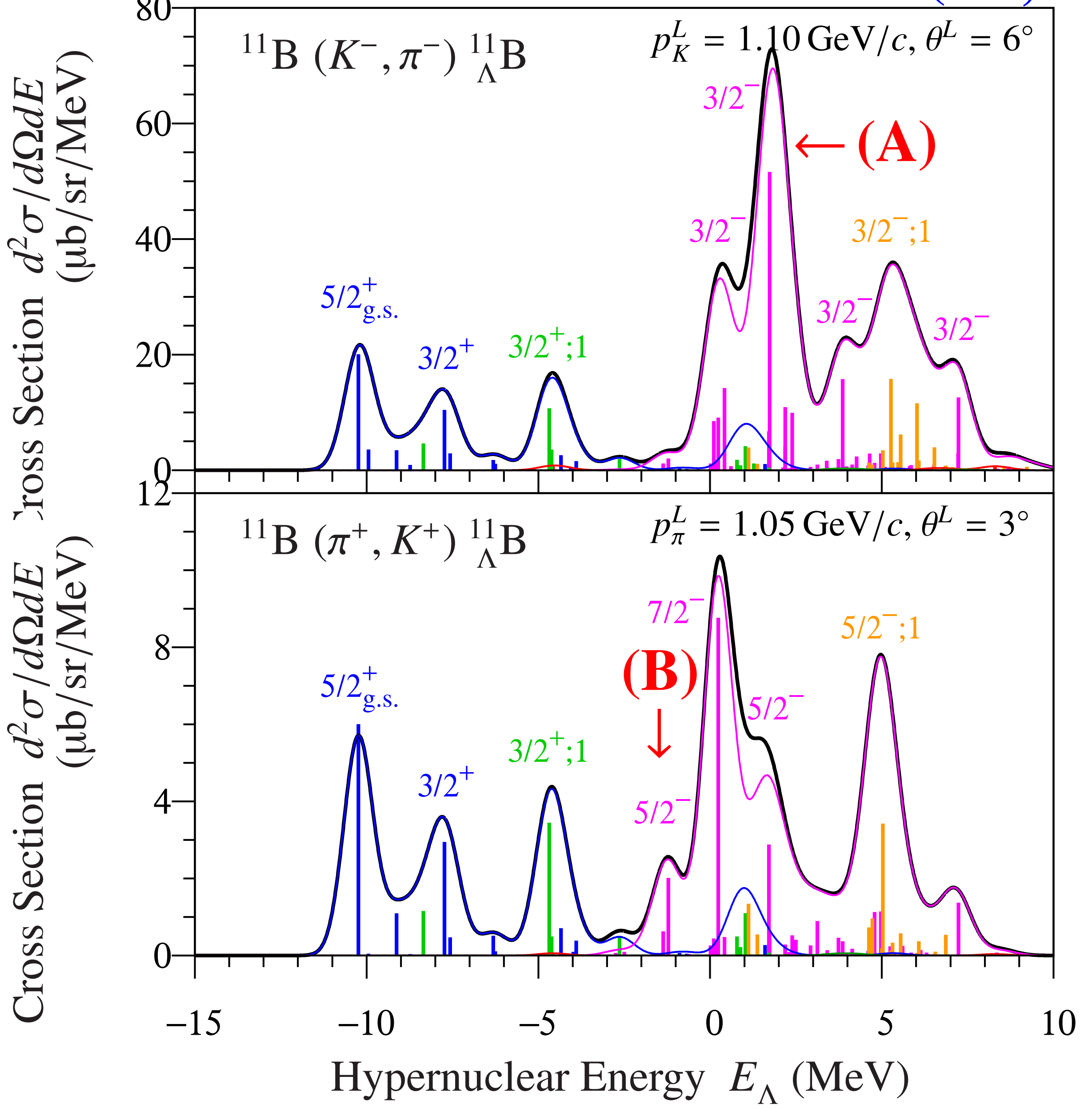
CONCLUDE:

$\alpha\alpha$-like core deformation causes splitting of p^Λ-states, then low-energy $p_{//}^\Lambda$ can mix with s^Λ-states.

$[^9\mathrm{Be}(J^-)\times\Lambda(p_{//})] + [^9\mathrm{Be}(J^+)\times\Lambda(s)]$

These parity-mixed wave functions at $E_\Lambda = 0$ MeV can explain the extra peak #a.

Results : Cross sections of the ^{11}B (K^-, π^-) and ^{11}B (π^+, K^+) reactions



(A) $3/2^-$

^{10}B$(3^+_{g.s.}) \otimes p^{\Lambda}_{3/2}$	51.4%
^{10}B$(1^+_2) \otimes p^{\Lambda}_{1/2}$	23.0%
^{10}B$(3^+_2) \otimes p^{\Lambda}_{3/2}$	9.4%

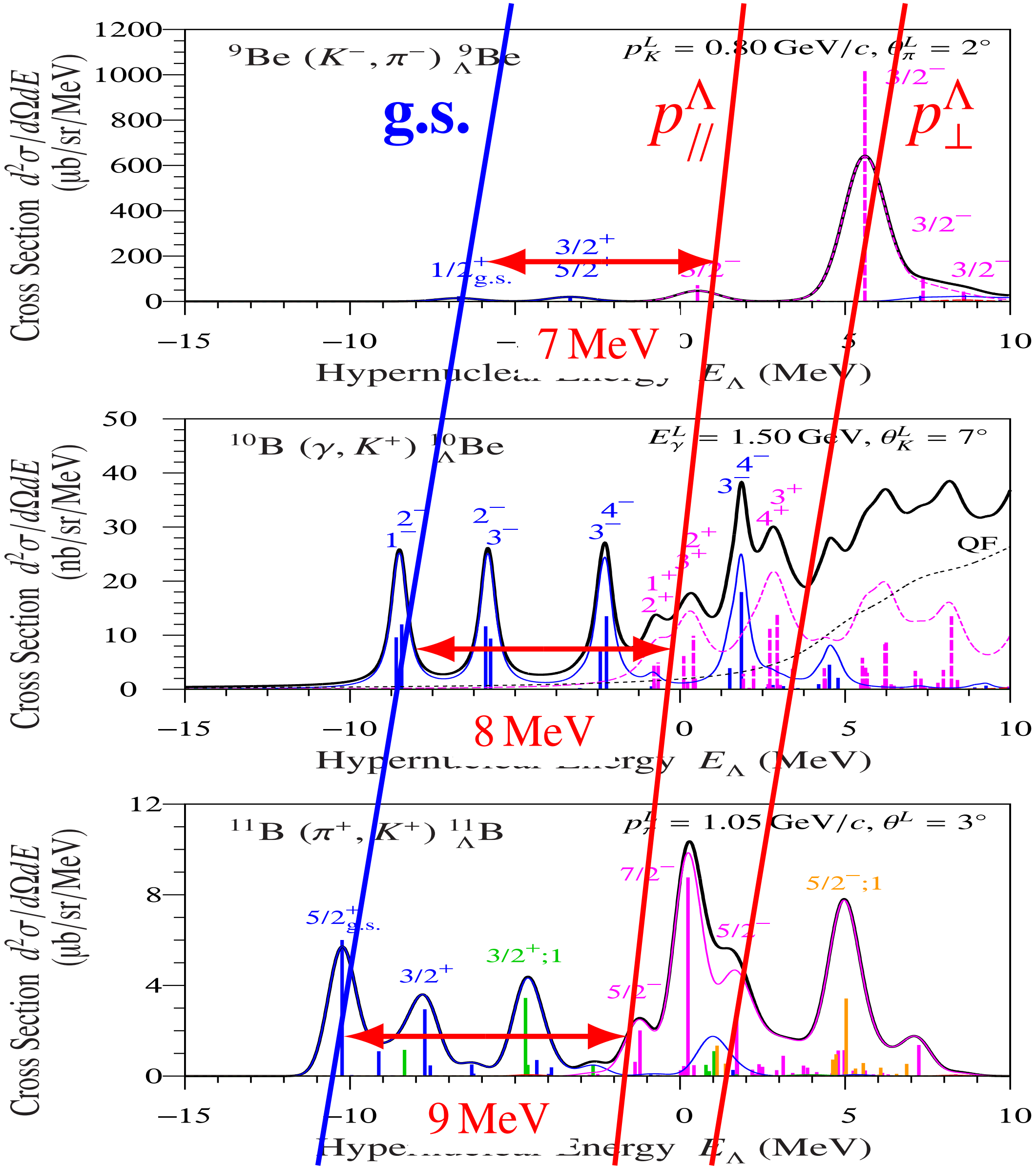
→ $p_\perp$ **state (substitutional)**

(B) $5/2^-$

^{10}B$(3^+_{g.s.}) \otimes p^{\Lambda}_{3/2}$	56.1%
^{10}B$(3^+_{g.s.}) \otimes p^{\Lambda}_{1/2}$	35.7%

→ $p_{//}$ **state**

Results : Energy of $p_{//}$-state



The p^Λ-state splits into $p_\perp$- and $p_{//}$-states due to the strong coupling with nuclear core deformation.

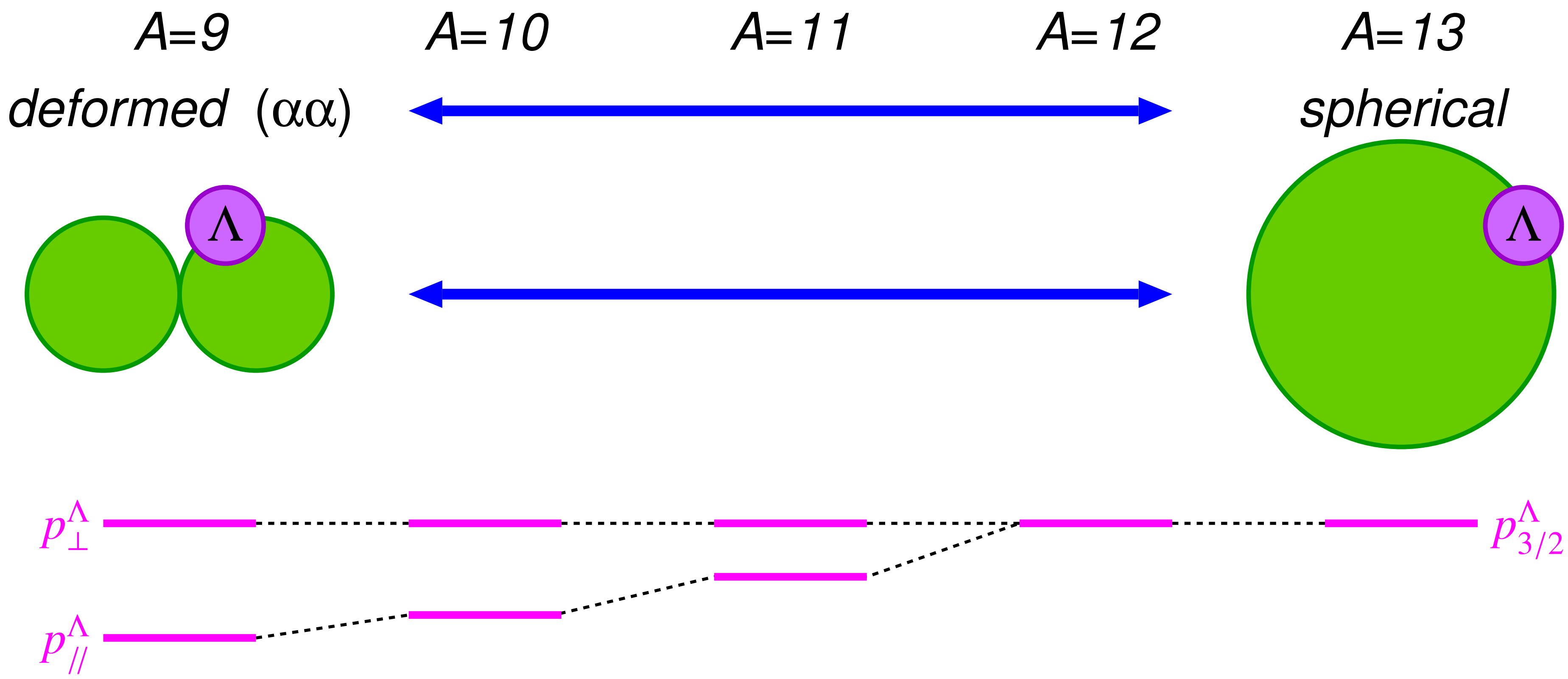
In $^{9}_{\Lambda}$Be, the enregy of $p^\Lambda_{//}$-state comes down to $E_x \approx 7$ MeV from the Λ single-particle energy difference $\varepsilon^\Lambda_p - \varepsilon^\Lambda_s \approx 11$ MeV.

The bump at $E_x \approx 8$ MeV in the cross sections of $^{10}_{\Lambda}$Be corresponds to the $p^\Lambda_{//}$-state.

In the cross sections of $^{11}_{\Lambda}$B, the small $5/2^-$ peak at $E_x \approx 9$ MeV corresponds to the $p^\Lambda_{//}$-state.

The energy splitting between $p_\perp$- and $p_{//}$-states in $^{11}_{\Lambda}$B is smaller than that in $^{9}_{\Lambda}$Be, which is due to the small deformation of the nuclear core in $^{11}_{\Lambda}$B.

p^{Λ} state in the deformed nuclear core



In the spherical nuclear core, p^{Λ}-state does not split into $p_{//}^{\Lambda}$ and $p_{\perp}^{\Lambda}$.

The new type wave function should appear in $^{9,10}_{\Lambda}$Be and $^{10,11}_{\Lambda}$B due to the core deformation, but "not" in spherical systems without enough deformation.

Summary

We have calculated the DWIA production cross sections for p-shell hypernuclei by using the extended shell model.

- **Strong coupling between p-state Λ and core deformation is realized in $^{9,10}_{\Lambda}\mathrm{Be}$ and $^{10,11}_{\Lambda}\mathrm{B}$.**
- **In these nuclei, p^{Λ}-state splits into $p^{\Lambda}_{//}$ and $p^{\Lambda}_{\perp}$.**
- **In $^{10}_{\Lambda}\mathrm{Be}$, the lower $p^{\Lambda}_{//}$ comes down in energy and $[^9\mathrm{Be}(J^-)\times\Lambda(p_{//})]$ couples easily with $[^9\mathrm{Be}(J^+)\times\Lambda(s)]$.**
- **Such new type wave functions should appear in $^{9,10}_{\Lambda}\mathrm{Be}$ and $^{10,11}_{\Lambda}\mathrm{B}$ due to the core deformation.**

The finding of peak #a in $^{10}\mathrm{B}\ (e,e'K^+)\ ^{10}_{\Lambda}\mathrm{Be}$ is a novel evidence for genuine hyper-nuclear wave function with parity-mixing realized in "deformed" hypernuclei.