Hypernuclear Investigation with Electromagnetic Interaction

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Reaction and structure of hypernuclei

Atsushi UMEYA (Nippon Inst. of Tech.)

collaborated with

Toshio MOTOBA (RCNP, Osaka Univ. / Osaka E-C Univ.)

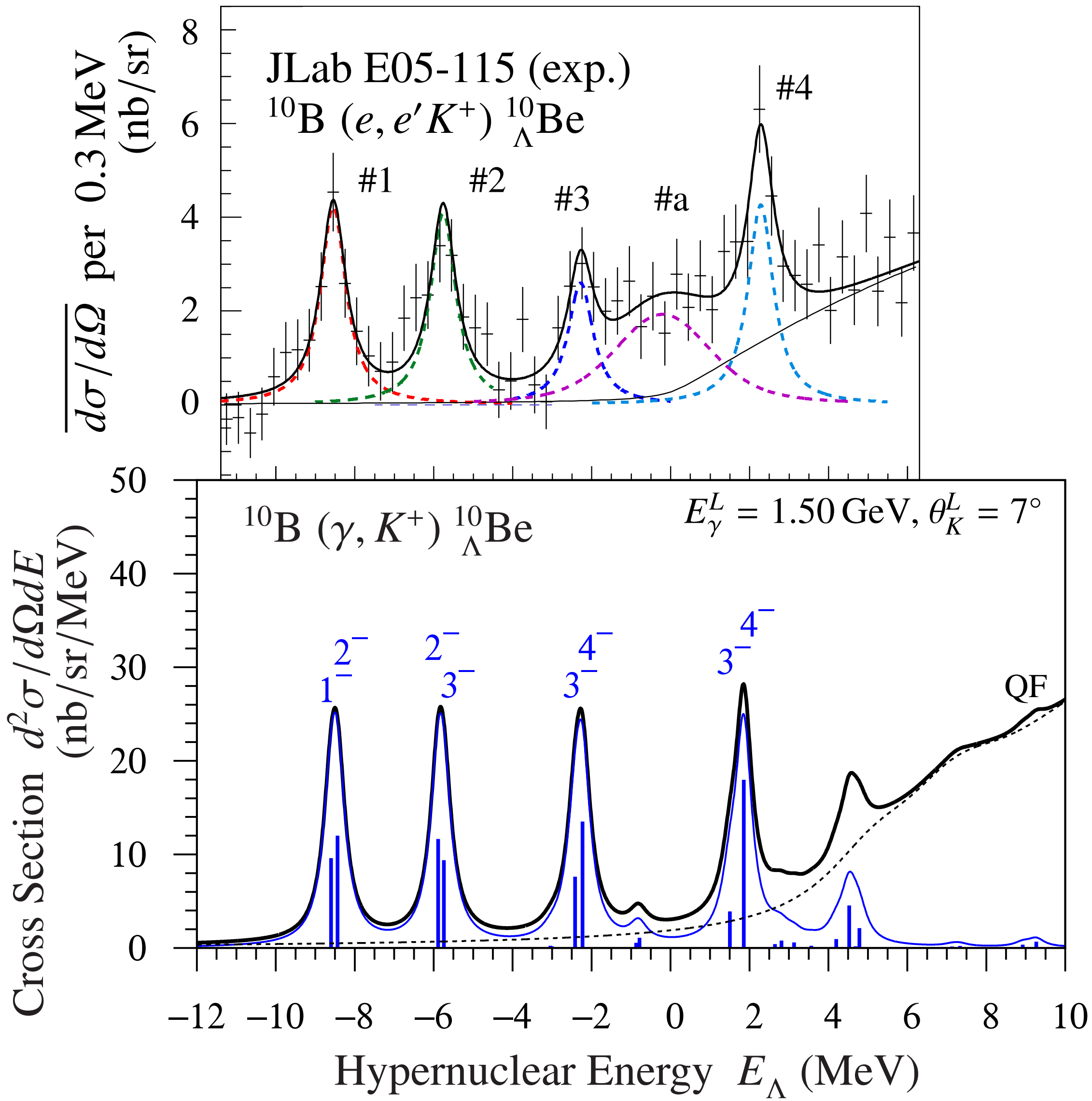
Kazunori ITONAGA (Miyazaki Univ. / Gifu Univ.)

Introduction

- **p-shell nuclei and hypernuclei provide a variety of interesting phenomena (shell-, cluster-, and coexistent characters), depending on E_x and mass.**
- **High-precision experiments in hypernuclear spectroscopy are in progress.**
- **Detailed look in Jlab $(e, e'K^+)$ spectroscopic data requires an extended description with multi-configuration parity-mixing mediated by hyperon.**

- **We have calculated the production cross sections for p-shell hypernuclei by using the extended shell model.**
- **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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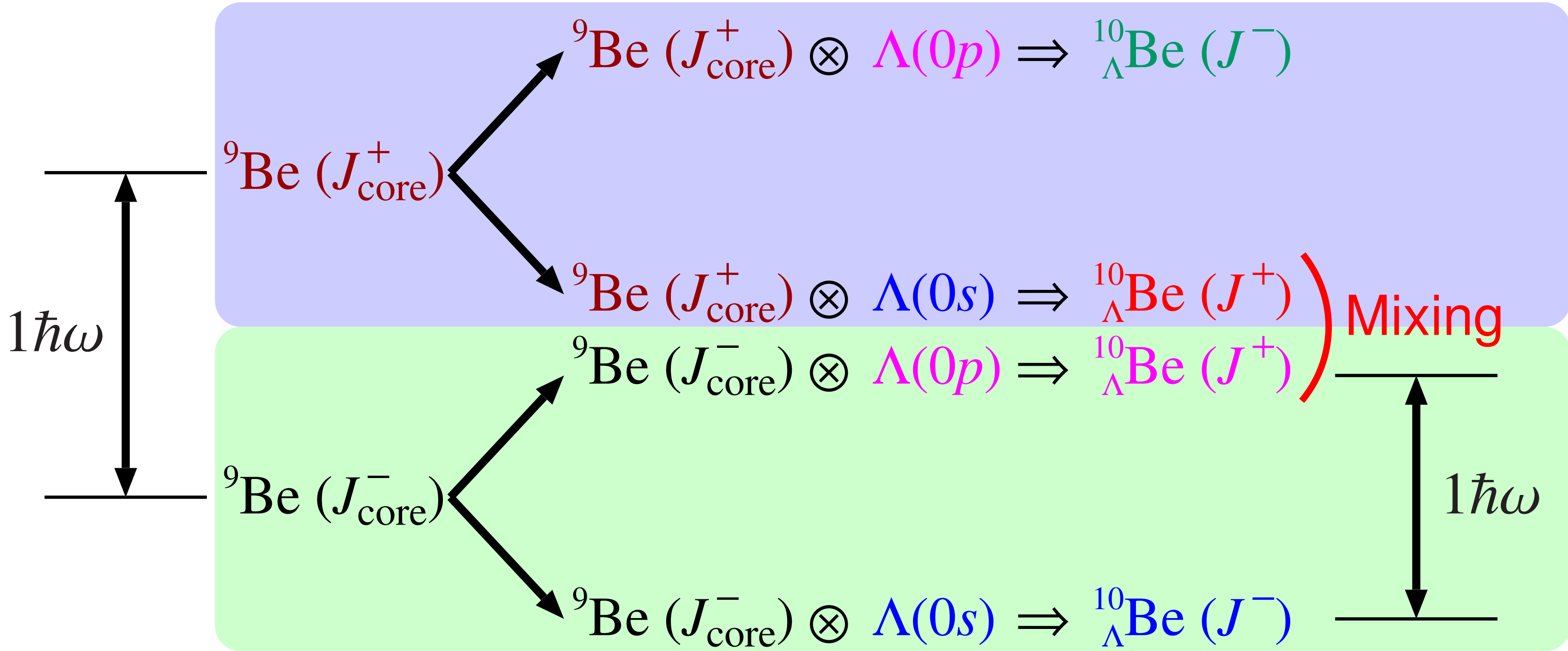
The extension of the model space is necessary and interesting challenge in view of the present hypernuclear spectroscopy.

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

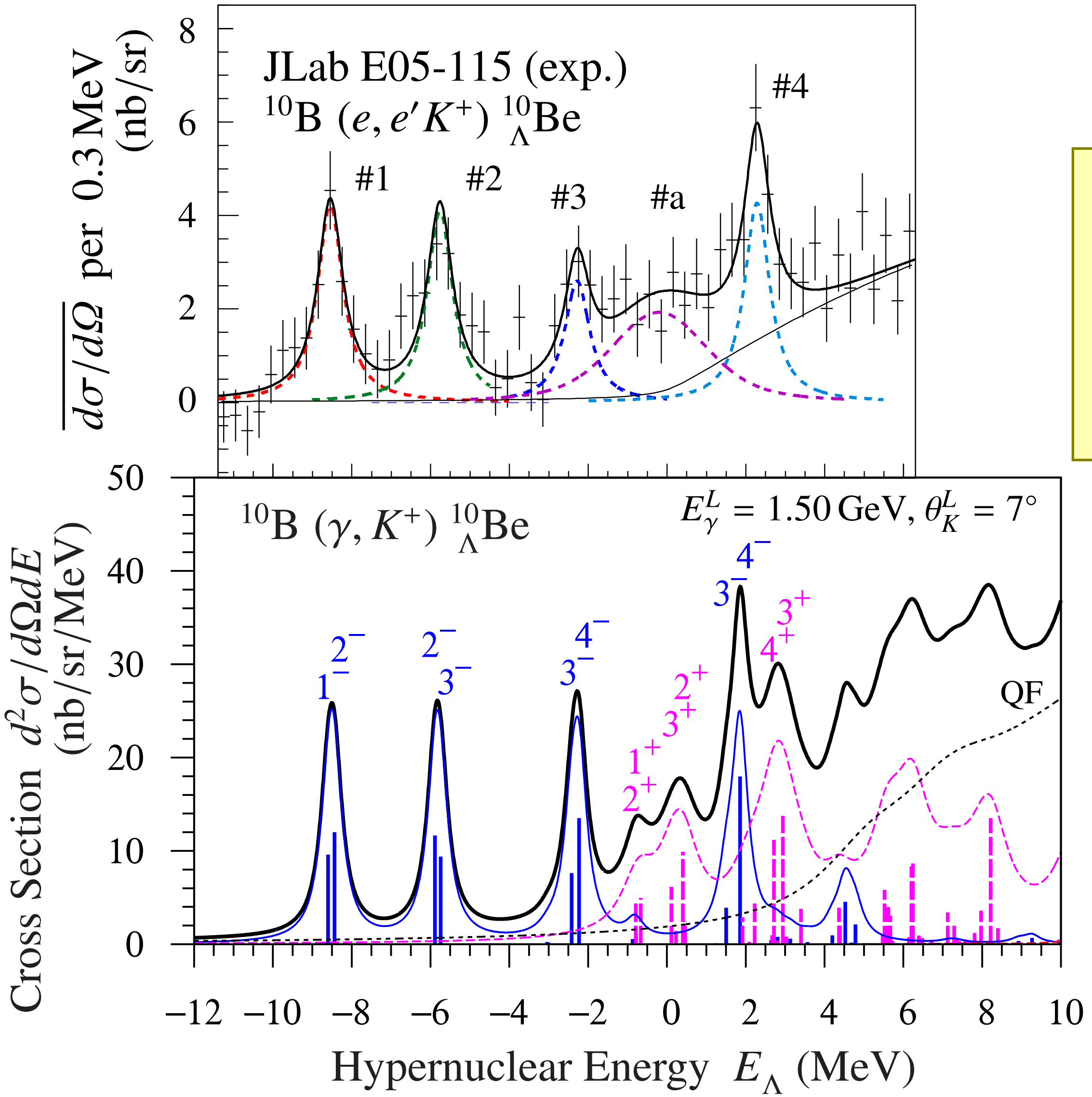


In the conventional shell model, only natural-parity nuclaer-core states ($J^{-}_{\rm core}$) are taken into account. Λ particle is in the 0*s* orbit in $^{10}_{\Lambda}$Be(J^{-}).

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

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

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



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

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

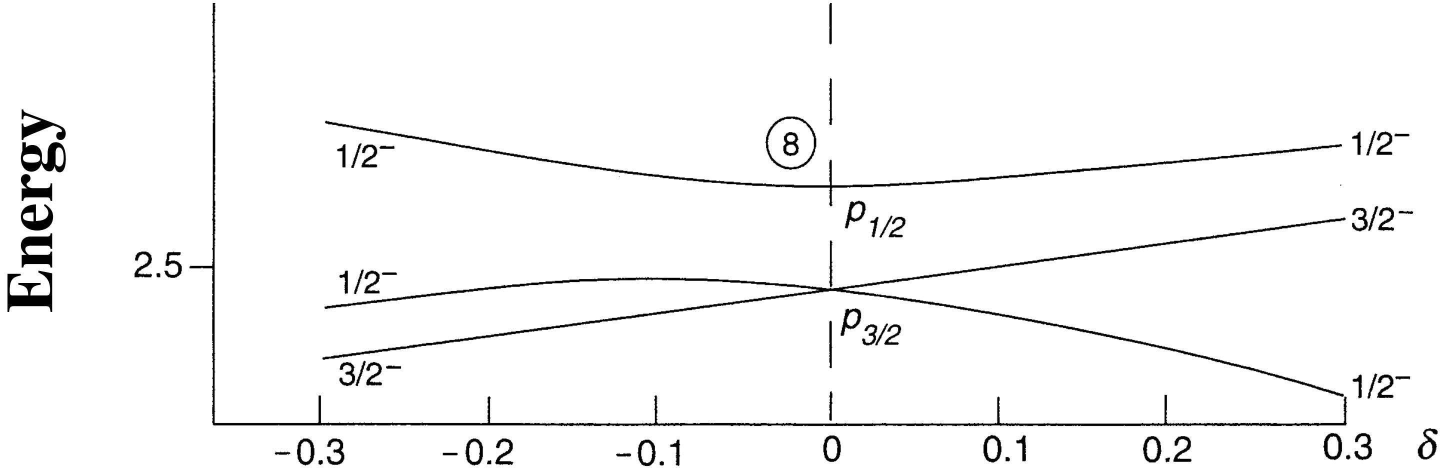
DWIA calculation by using Saclay-Lyon model A

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.

Splitting of *p*-state in the deformed nuclei

The bump in the cross sections of $^{10}_{\Lambda}\mathrm{Be}$ will be explained by the splitting of p^{Λ}-state in the deformed core-nucleus.



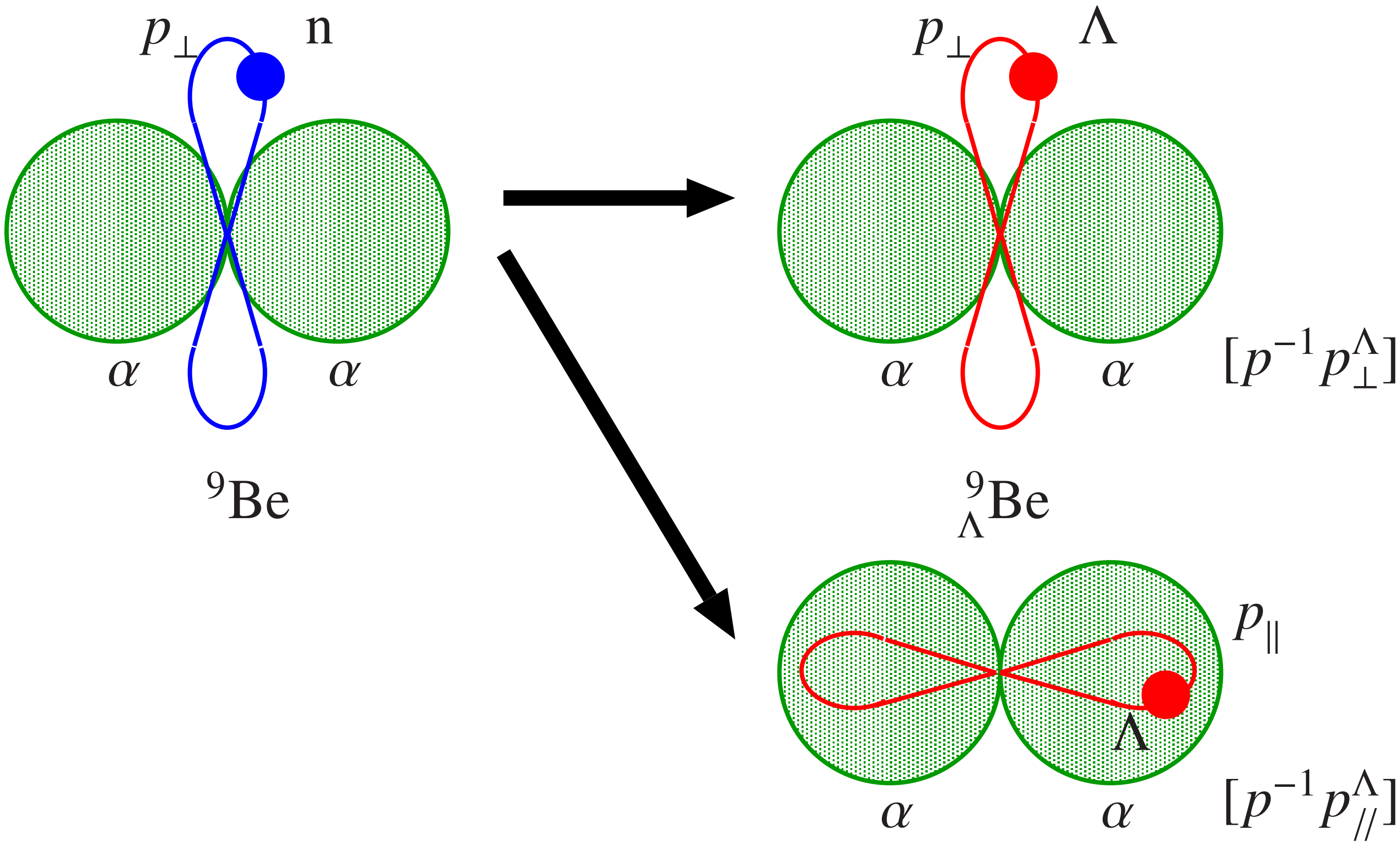
Deformation parameter δ

S. G. Nilsson, Mat. Fis. Medd. Dan. Vid. Selsk. 29 (1955) No. 16

Eigenvalues Ω of z-component of angular momentum operator and parities are good quantum numbers in the Nilsson diagram.

$$p_{3/2} \to \Omega^{\pi} = 1/2^{-}, 3/2^{-}$$

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



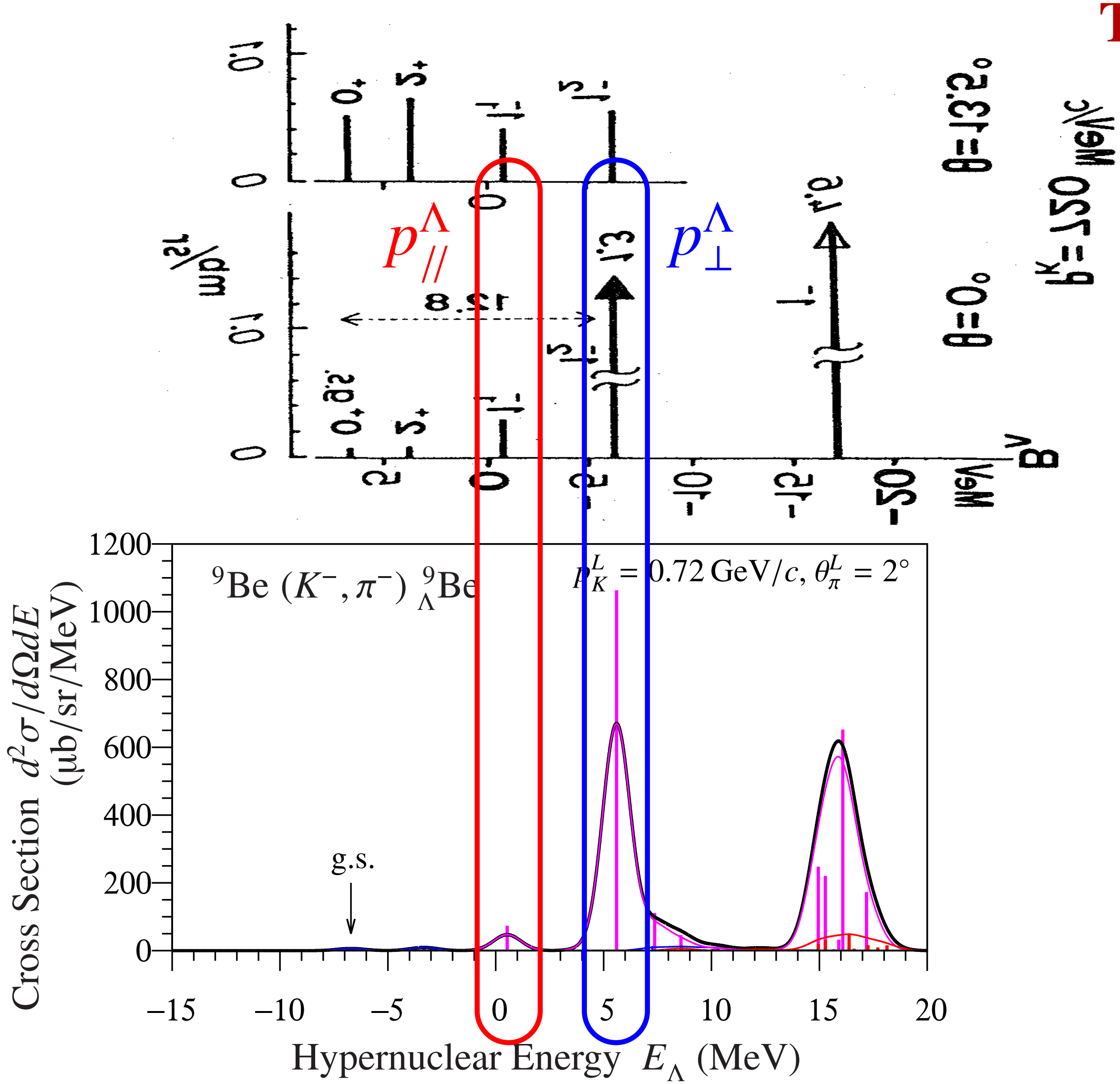
In ${}^{9}_{\Lambda}$Be, it is well known that the p_{Λ}-state splits into two orbital states expressed by $p_{\perp}$ and $p_{//}$, which is due to the strong coupling with nuclear core deformation having the α-α structure.

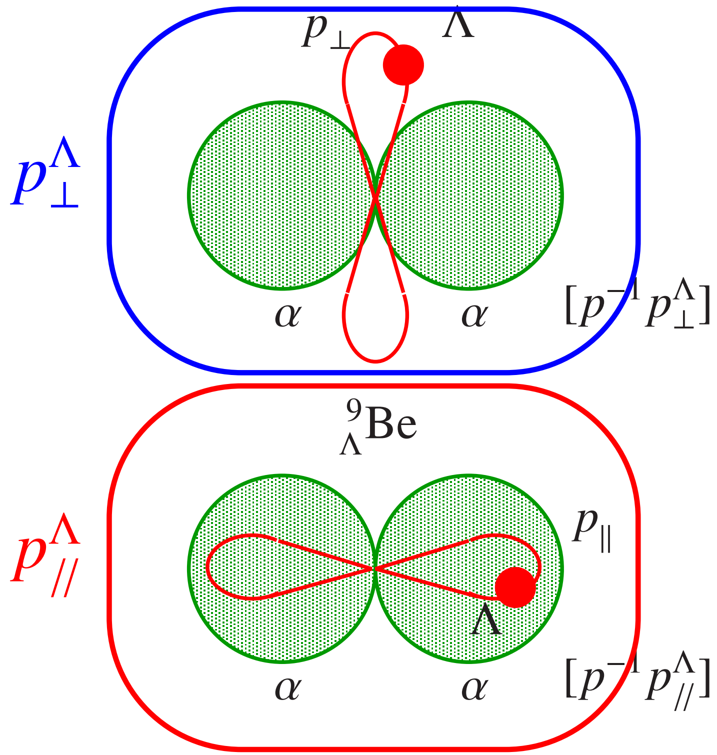
T. Motoba *et al.*, PTPS81, 42 (1985)

R. H. Dalitz, A. Gal, PRL36, 362 (1976); AP131, 314 (1981)

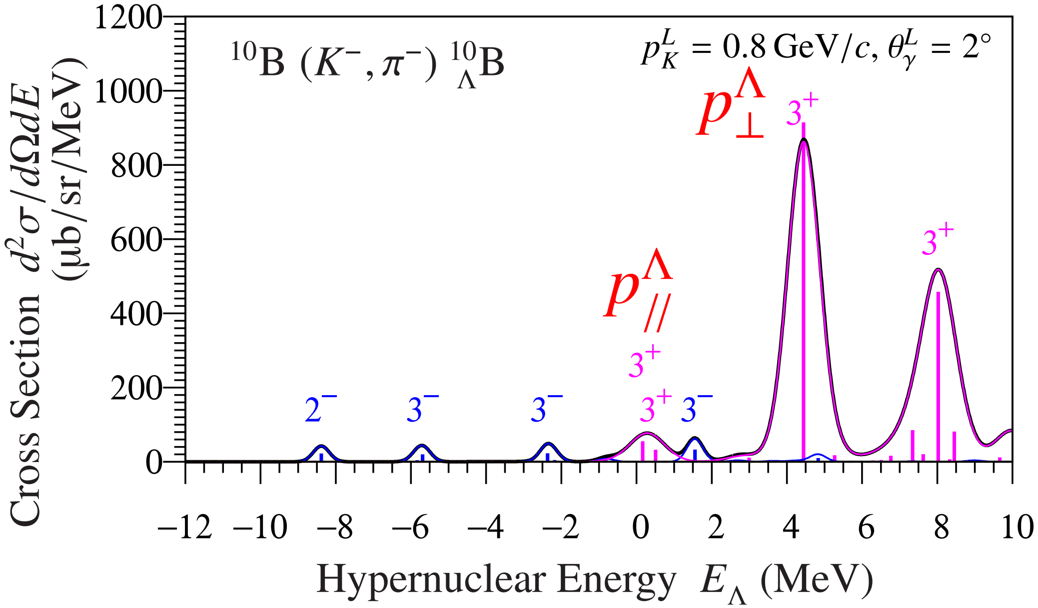
Results : Comparison to the cluster model – Cross section –

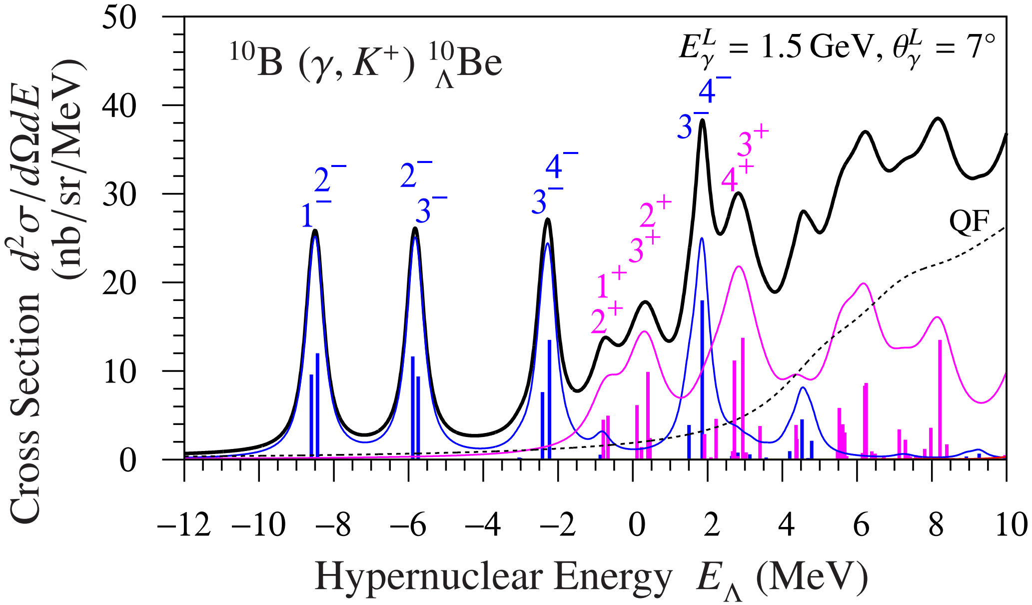
T. Motoba *et al.*, PTPS81, 42 (1985)





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





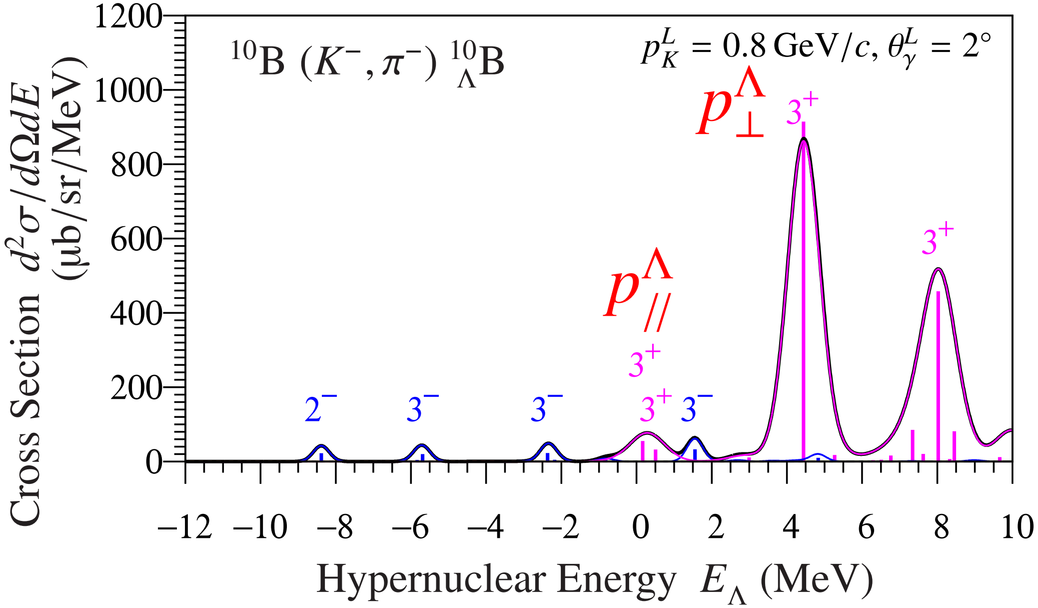
In the (K^-,π^-) reaction, the large peak at $E_\Lambda = 4.4$ MeV is a p-substitutional state via the $p^N_{3/2} \to p^\Lambda_{3/2}$, which is strongly excited by recoilless reaction.

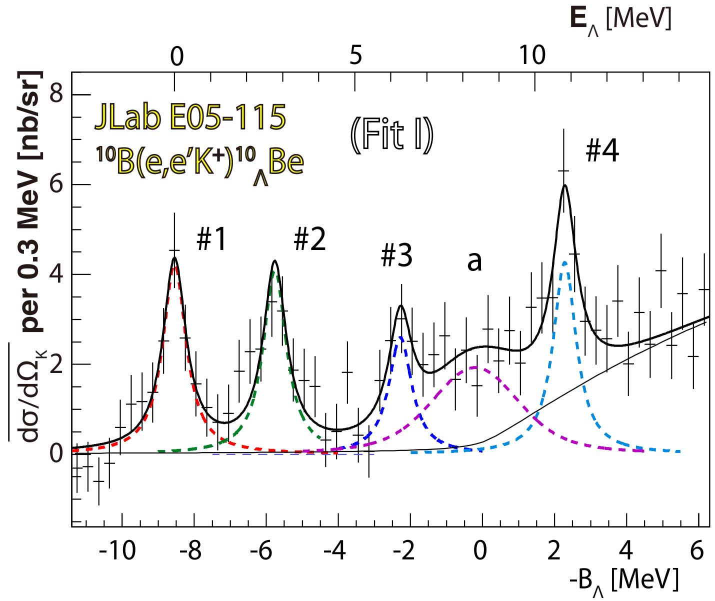
The small peak at $E_\Lambda = 0$ MeV corresponds to the new bump and is explained as a mixture of s^Λ and p^Λ states.

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}B (K^-,π^-) $^{10}_{\Lambda}$B reaction (2)





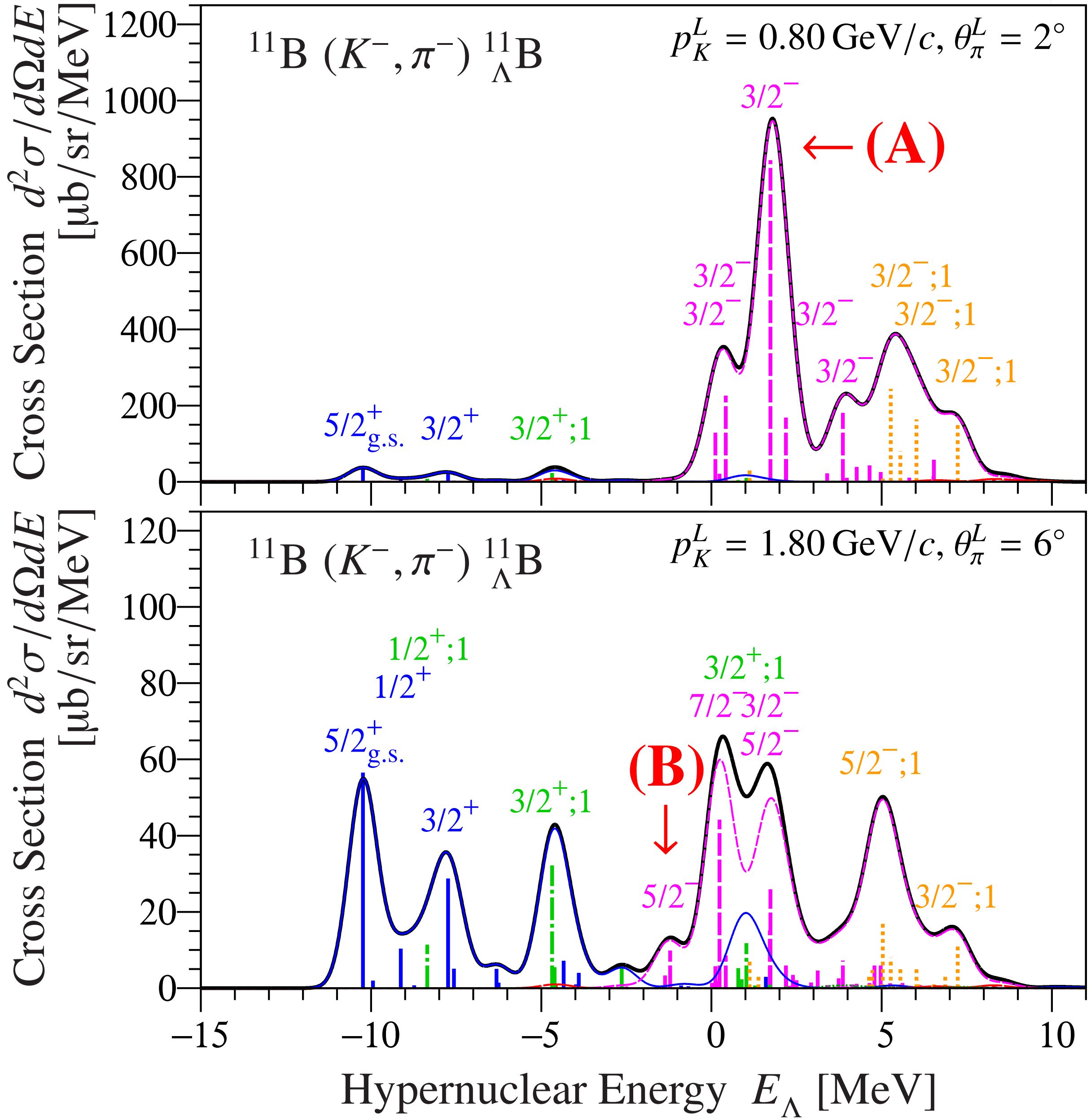
CONCLUDE:

$\alpha\alpha$-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^-) $^{11}_{\Lambda}$B reaction (1)



FWHM = 1.0 MeV

- T=0, J^+; $J^+_{core} \otimes s_\Lambda$
- T=1, J^+; $J^+_{core} \otimes s_\Lambda$
- T=0, J^-; $J^+_{core} \otimes p_\Lambda$
- T=1, J^-; $J^+_{core} \otimes p_\Lambda$

(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%

→ **substitutional state**

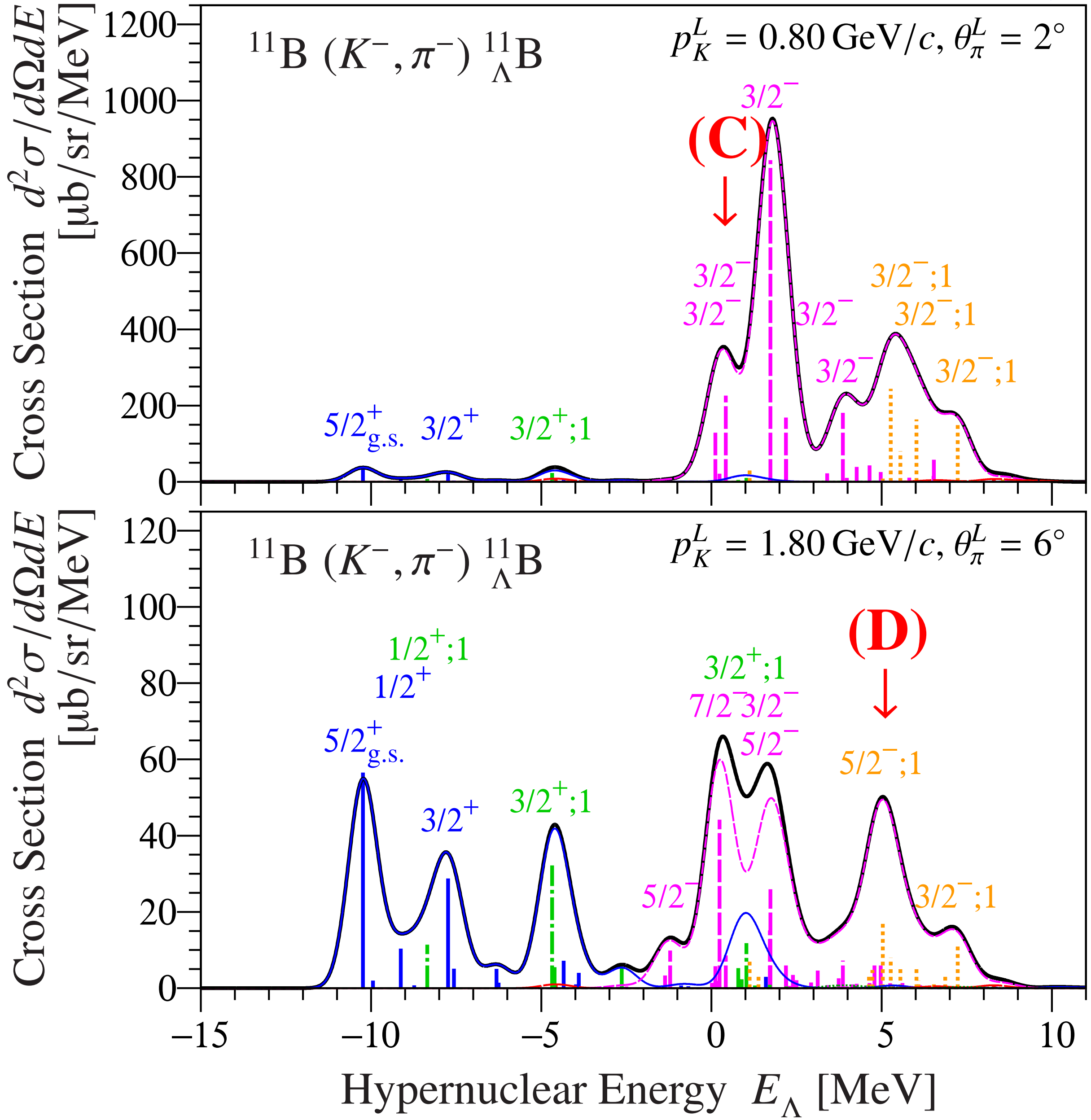
(B) $5/2^-$

^{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**

ΛN int. is strong coupling for p^Λ as in the case of $^{9}_{\Lambda}$Be

Results : Cross sections of the $^{11}\mathrm{B}\,(K^-,\pi^-)\,^{11}_{\Lambda}\mathrm{B}$ reaction (2)



(C) $3/2^-$

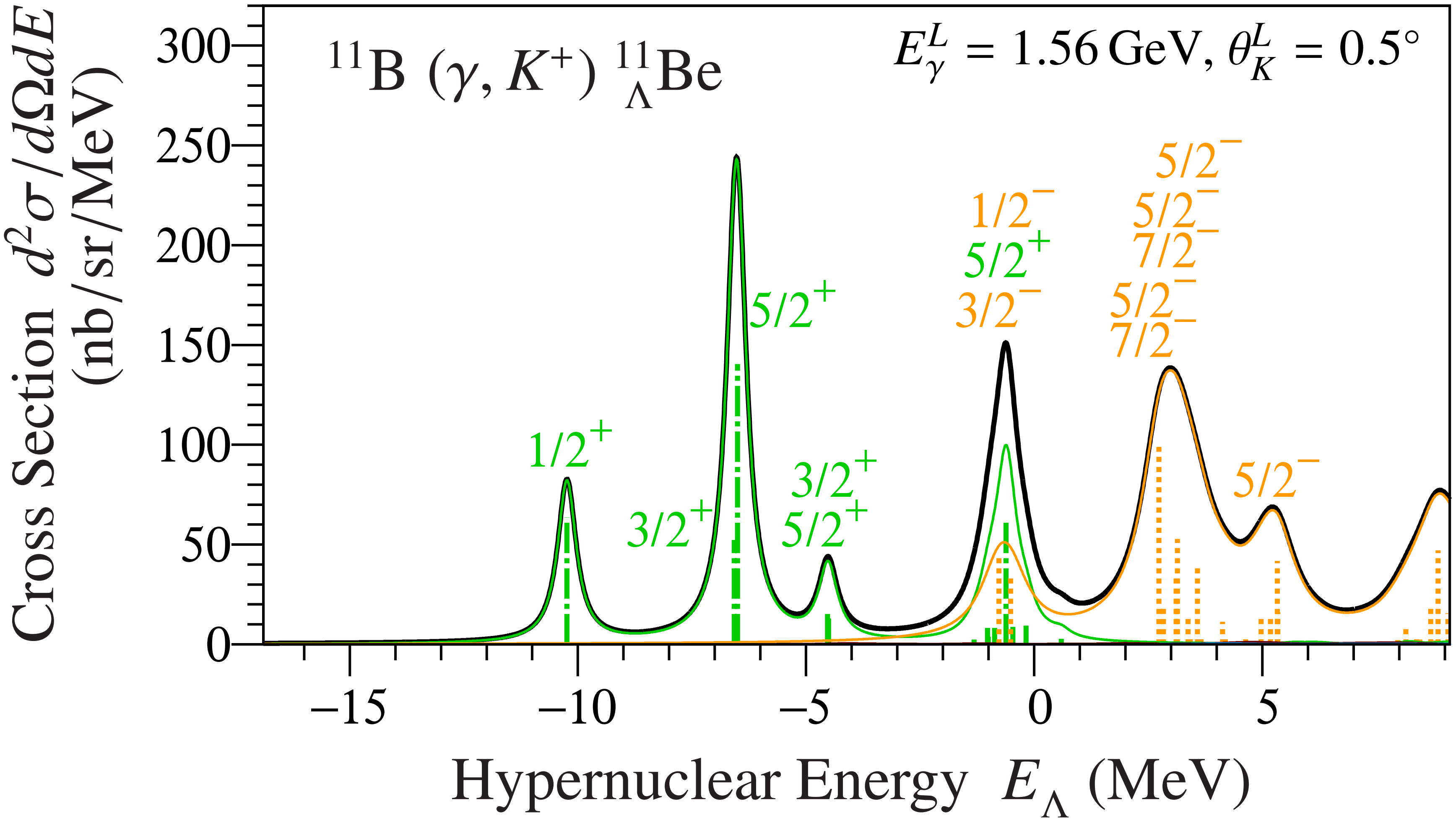
$^{10}\mathrm{B}(2^-_3) \otimes s^\Lambda_{1/2}$	31.6%
$^{10}\mathrm{B}(3^+_{g.s.}) \otimes p^\Lambda_{3/2}$	11.1%
$^{10}\mathrm{B}(1^+_1) \otimes p^\Lambda_{1/2}$	46.9%

(D) $5/2^-(T=1)$

$^{10}\mathrm{B}(3^-_3; T=1) \otimes s^\Lambda_{1/2}$	21.2%
$^{10}\mathrm{B}(2^+_1; T=1) \otimes p^\Lambda_{3/2}$	29.3%
$^{10}\mathrm{B}(2^+_1; T=1) \otimes p^\Lambda_{1/2}$	42.0%

large parity mixing in the core nucleus

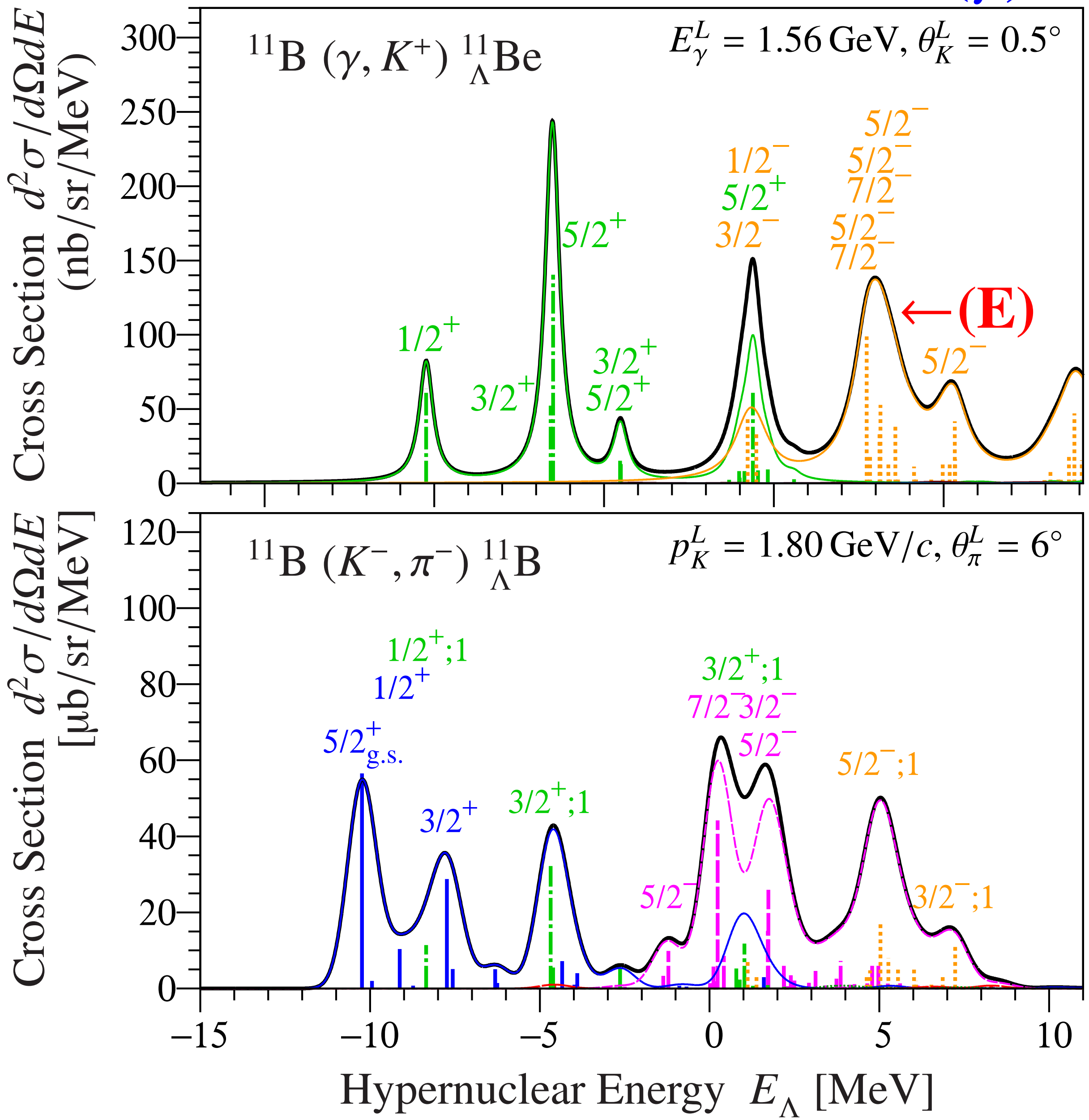
Results : Cross sections of the ^{11}B (γ, K^+) $^{11}_{\Lambda}$Be reaction (1)



without QF, FWHM = 1.0 MeV

dominant configurations **green** $T=1, J^+; J^+_{\rm core} \otimes s_\Lambda$ **orange** $T=1, J^-; J^+_{\rm core} \otimes p_\Lambda$

Results : Cross sections of the $^{11}B\,(\gamma, K^+)\,^{11}_{\Lambda}Be$ reaction (2)



(E-1) $5/2^-(T=1)$

$^{10}Be(3^-_3)\otimes s^\Lambda_{1/2}$ 73.7%

$^{10}Be(2^+_1)\otimes p^\Lambda_{3/2}$ 4.2%

$^{10}Be(2^+_1)\otimes p^\Lambda_{1/2}$ 17.9%

(E-2) $5/2^-(T=1)$

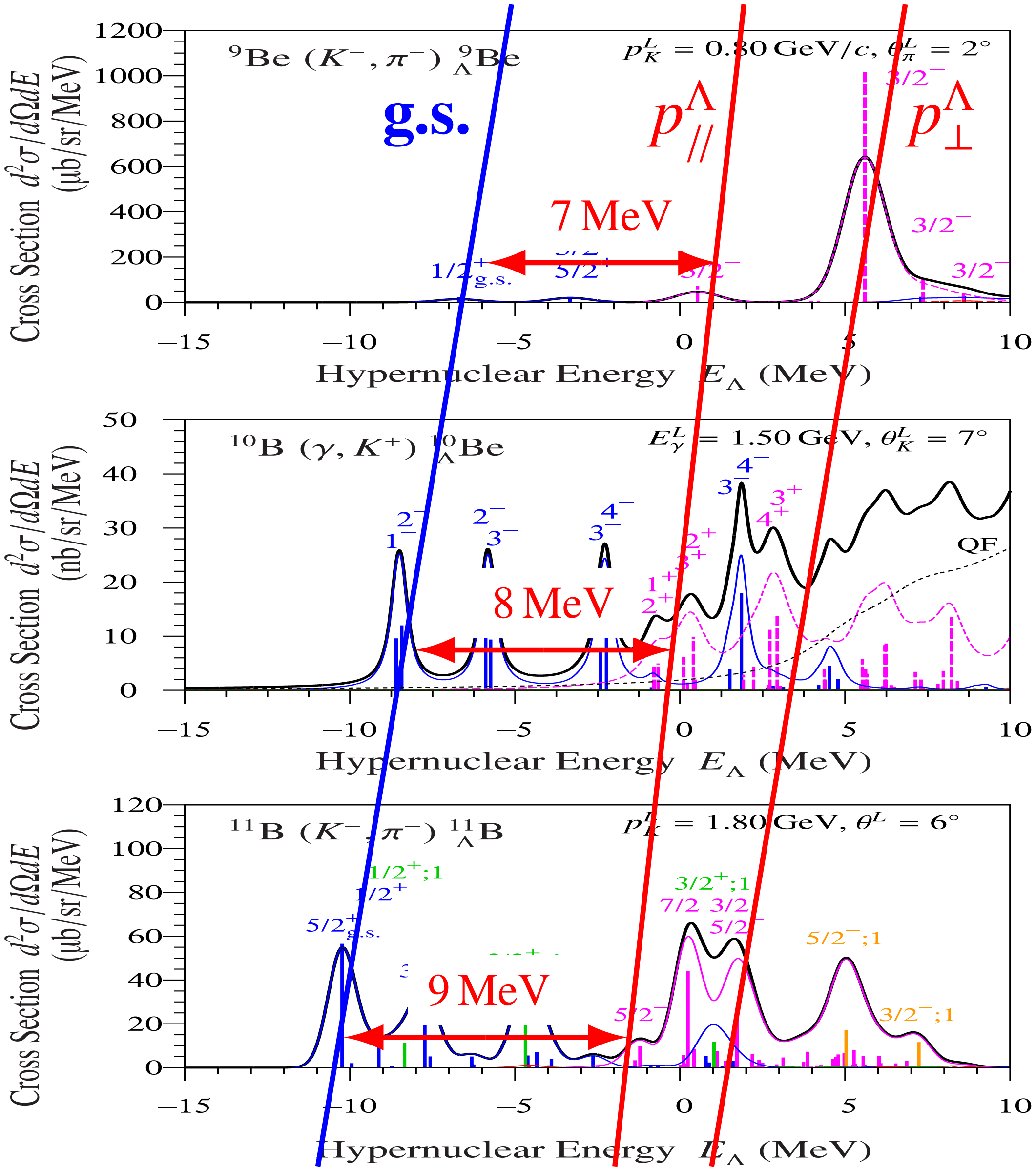
$^{10}Be(3^-_3)\otimes s^\Lambda_{1/2}$ 21.2%

$^{10}Be(2^+_1)\otimes p^\Lambda_{3/2}$ 29.3%

$^{10}Be(2^+_1)\otimes p^\Lambda_{1/2}$ 42.0%

large parity mixing in the core nucleus

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.

Summary

We have calculated the energy levels and the 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 $^{9,10,11}_{\Lambda}\mathrm{Be}$ 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 $^{9,10,11}_{\Lambda}\mathrm{Be}$ 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 hypernuclear wave function with parity-mixing realized in "deformed" hypernuclei.