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Hypernuclear spectroscopy with extended shell-model configurations

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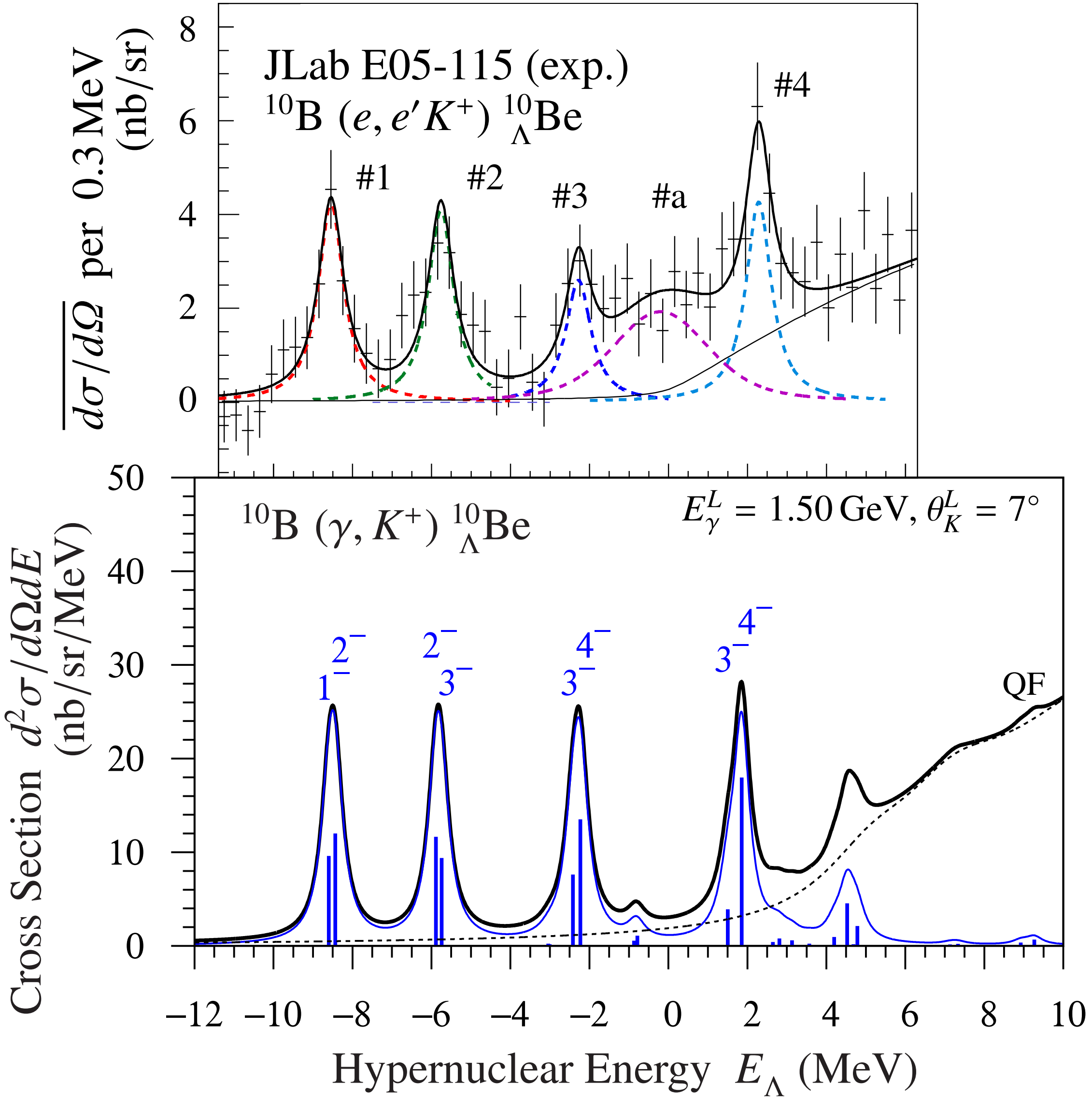
Basic motivations

- **Hypernuclear studies have played an important role to understand hyperon-nucleon fundamental interaction properties and also to disclose characteristic structures of many-nucleon systems with strange particles which are free from the nucleon Pauli principle.**

- **In various theoretical approaches in hypernuclear spectroscopy, different types of production cross sections are often compared in order to elucidate properties of many-body structures.**

- **We focus our attention on the understanding of the new results of high-resolution $(e, e'K^+)$ experiments done at the Jefferson Laboratory (JLab) and then we will also discuss possibility of high-resolution (π^+, K^+) and (K^-, π^-) reactions being planned in the upgrade proposal of the J-PARC beamlines.**

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



Recent experimental result

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

Shell-model prediction

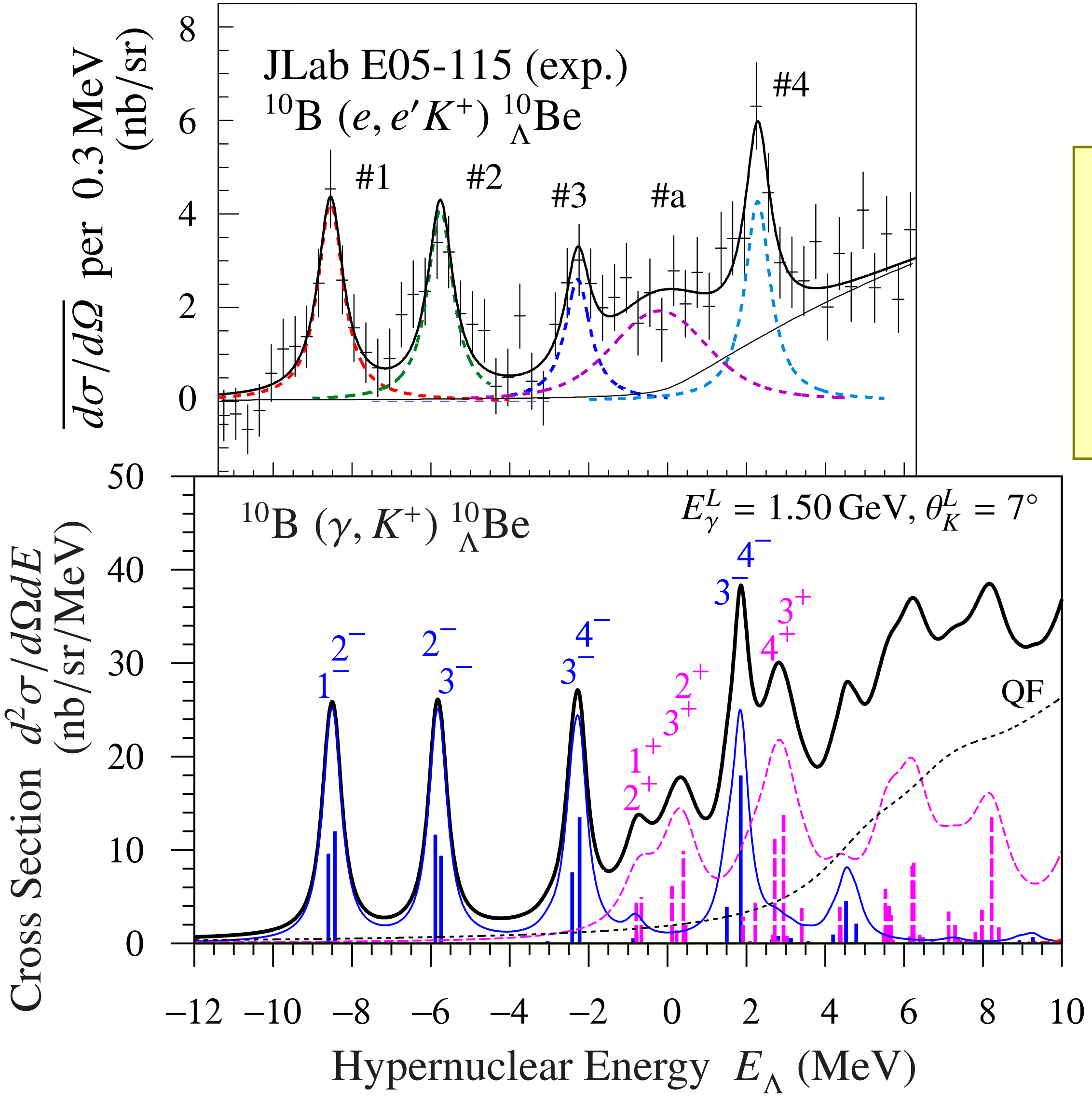
T. Motoba *et al.*, PTPS117, 123 (1994)

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

This experiment has confirmed the major peaks (#1, #2, #3, #4) predicted by the DWIA calculations based on the normal-parity nuclear core wave functions coupled with a Λ-hyperon in *s*-orbit.

At the same time, the data also show an extra subpeak (#a) which seem difficult to be explained within the *p*-shell nuclear normal parity configurations employed so far.

Model space extension for the extra subpeak



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

In order to describe the extra subpeak, we have extended the model space by introducing the new configuration which includes non-normal parity nuclear core-excited states.

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 talk

For the $^{11}_{\Lambda}\mathrm{B}$ and $^{11}_{\Lambda}\mathrm{Be}$ hypernuclei, we will show the energy levels and the DWIA cross-sections of (K^-, π^-) and (γ, K^+) reactions that are calculated within the extended model space.

Also, we will show the M1, E2, and E1 transtion strengths for these hypernuclei.

Extension of the model space in the shell model ($^{11}_{\Lambda}$B case)

Model space for ^{10}B core

(A) conventional model space $J^{+}_{\rm core}$ $\boxed{(0s)^4\,(0p)^6}$ $(0p\text{-}0h)$

(B) extended model space $J^{-}_{\rm core}$ $\boxed{(0s)^3\,(0p)^7} \oplus \boxed{(0s)^4\,(0p)^5\,(sd)^1}$ $(1p\text{-}1h)$

Conventional model space for $^{11}_{\Lambda}$B

(I) $\boxed{J^{+}_{\rm core} \otimes 0s^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{+})$ **(II)** $\boxed{J^{+}_{\rm core} \otimes 0p^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{-})$

Extension (1) 1*p*-1*h* (1$\hbar\omega$) core excitation is taken into account

(a) $\boxed{J^{+}_{\rm core} \otimes 0s^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{+})$ **(b)** $\boxed{J^{+}_{\rm core} \otimes 0p^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{-})$

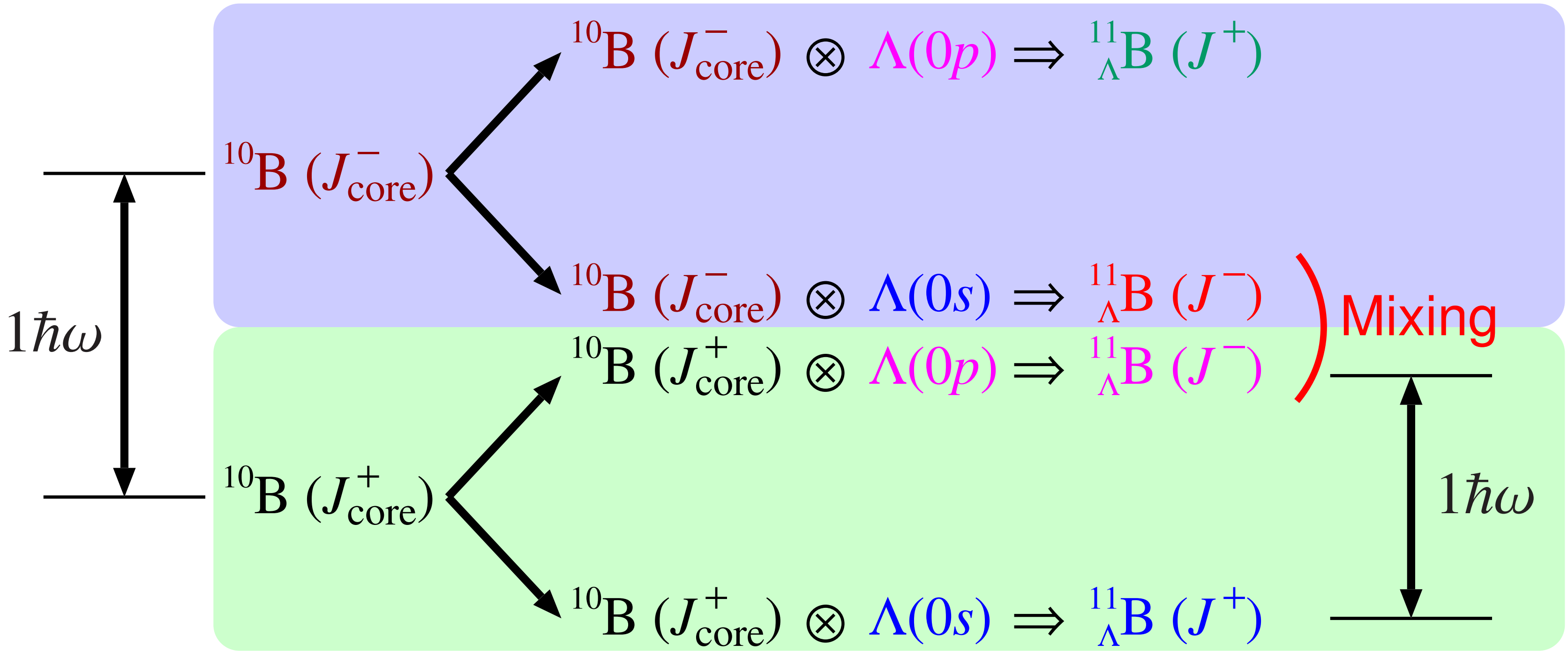
(c) $\boxed{J^{-}_{\rm core} \otimes 0s^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{-})$ **(d)** $\boxed{J^{-}_{\rm core} \otimes 0p^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{+})$

Extension (2) Configrations mixed by ΛN interaction

$$\boxed{J^{+}_{\rm core} \otimes 0s^{\Lambda}} \oplus \boxed{J^{-}_{\rm core} \otimes 0p^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{+})$$

$$\boxed{J^{+}_{\rm core} \otimes 0p^{\Lambda}} \oplus \boxed{J^{-}_{\rm core} \otimes 0s^{\Lambda}} \Rightarrow {}^{11}_{\Lambda}{\rm B}(J^{-})$$

Configration mixing in ${}^{11}_{\Lambda}\mathrm{B}$ unnatural parity states



$^{10}\mathrm{B}\ (J^-_{\rm core})$

$^{10}\mathrm{B}\ (J^-_{\rm core}) \otimes \Lambda(0p) \Rightarrow {}^{11}_{\Lambda}\mathrm{B}\ (J^+)$

$^{10}\mathrm{B}\ (J^-_{\rm core}) \otimes \Lambda(0s) \Rightarrow {}^{11}_{\Lambda}\mathrm{B}\ (J^-)$

$^{10}\mathrm{B}\ (J^+_{\rm core}) \otimes \Lambda(0p) \Rightarrow {}^{11}_{\Lambda}\mathrm{B}\ (J^-)$

Mixing

$1\hbar\omega$

$^{10}\mathrm{B}\ (J^+_{\rm core})$

$^{10}\mathrm{B}\ (J^+_{\rm core}) \otimes \Lambda(0s) \Rightarrow {}^{11}_{\Lambda}\mathrm{B}\ (J^+)$

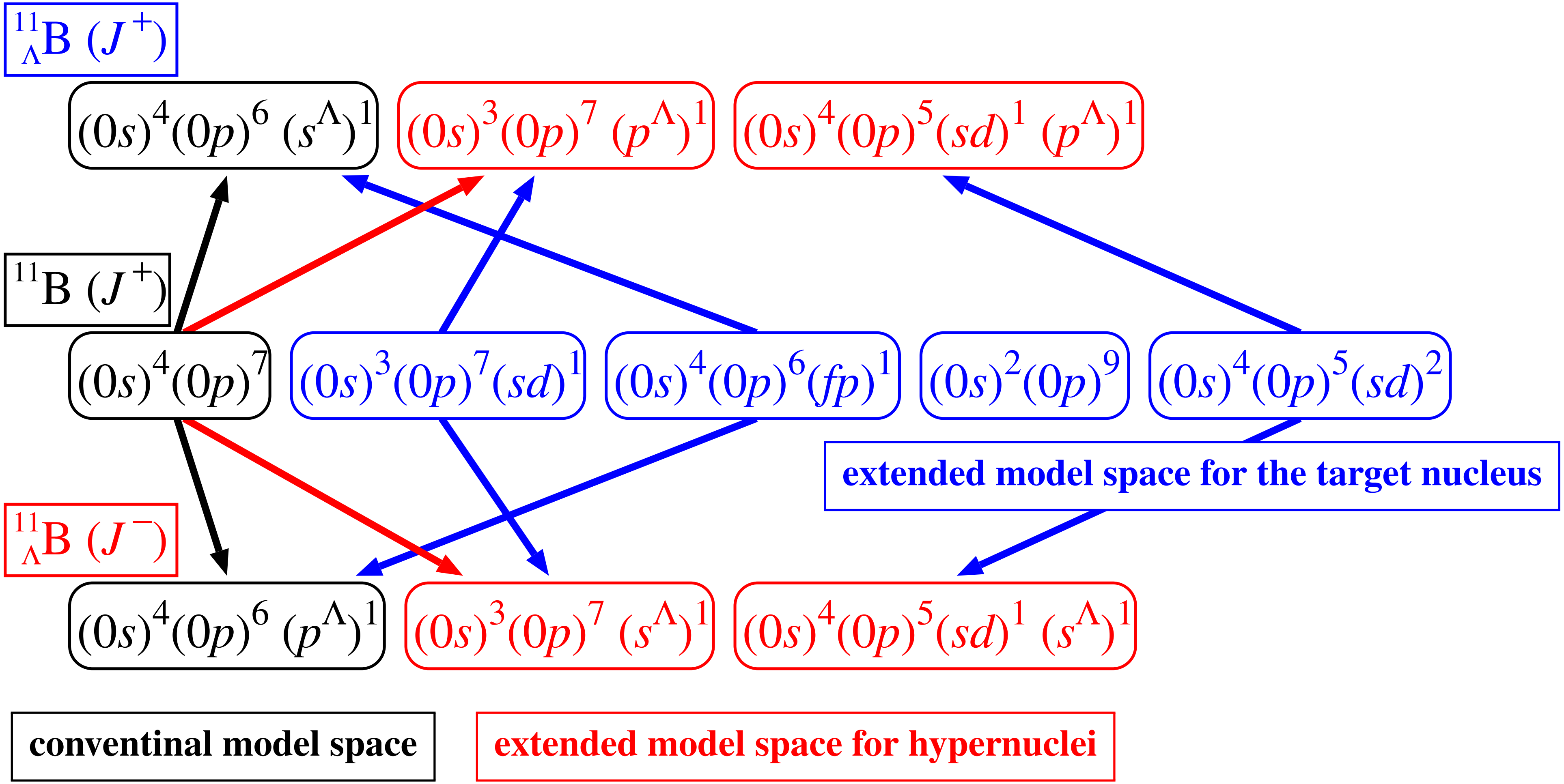
$1\hbar\omega$

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 ${}^{11}_{\Lambda}\mathrm{B}(J^+)$.

In ${}^{11}_{\Lambda}\mathrm{B}(J^-)$, the energy difference between $\Lambda(0s)$ and $\Lambda(0p)$ is $1\hbar\omega$, and the energy difference between $^{10}\mathrm{B}(J^+_{\rm core})$ and $^{10}\mathrm{B}(J^-_{\rm core})$ is $1\hbar\omega$.

By ΛN interaction, natural-parity nuclaer-core configurations and unnatural-parity nuclaer-core configurations can be mixed.

Extended model space for target nucleus $^{11}\mathrm{B}$



$^{11}_{\Lambda}\mathrm{B}\ (J^{+})$

$(0s)^4(0p)^6\,(s^{\Lambda})^1$

$(0s)^3(0p)^7\,(p^{\Lambda})^1$

$(0s)^4(0p)^5(sd)^1\,(p^{\Lambda})^1$

$^{11}\mathrm{B}\ (J^{+})$

$(0s)^4(0p)^7$

$(0s)^3(0p)^7(sd)^1$

$(0s)^4(0p)^6(fp)^1$

$(0s)^2(0p)^9$

$(0s)^4(0p)^5(sd)^2$

extended model space for the target nucleus

$^{11}_{\Lambda}\mathrm{B}\ (J^{-})$

$(0s)^4(0p)^6\,(p^{\Lambda})^1$

$(0s)^3(0p)^7\,(s^{\Lambda})^1$

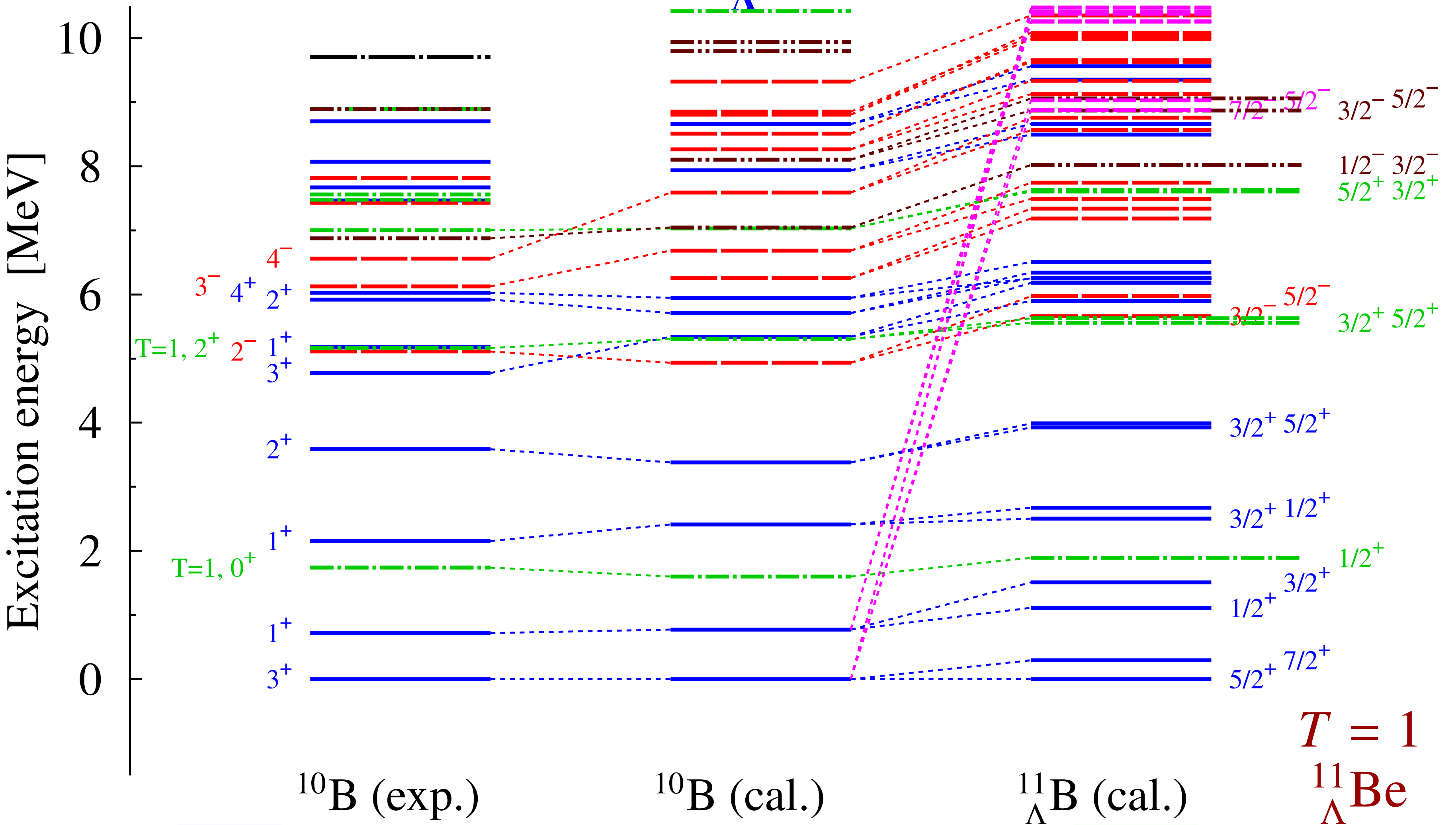
$(0s)^4(0p)^5(sd)^1\,(s^{\Lambda})^1$

conventinal model space

extended model space for hypernuclei

Extension of model space for target nucleus $^{11}\mathrm{B}$ up to $2p$-$2h$ ($2\hbar\omega$) allows the $^{11}_{\Lambda}\mathrm{B}$ production through various configurations.

Results : Energy levels of ^{10}B and $^{11}_{\Lambda}$B (1)



dominant configurations

blue $T=0, J^+; J^+_{\rm core} \otimes s_\Lambda$

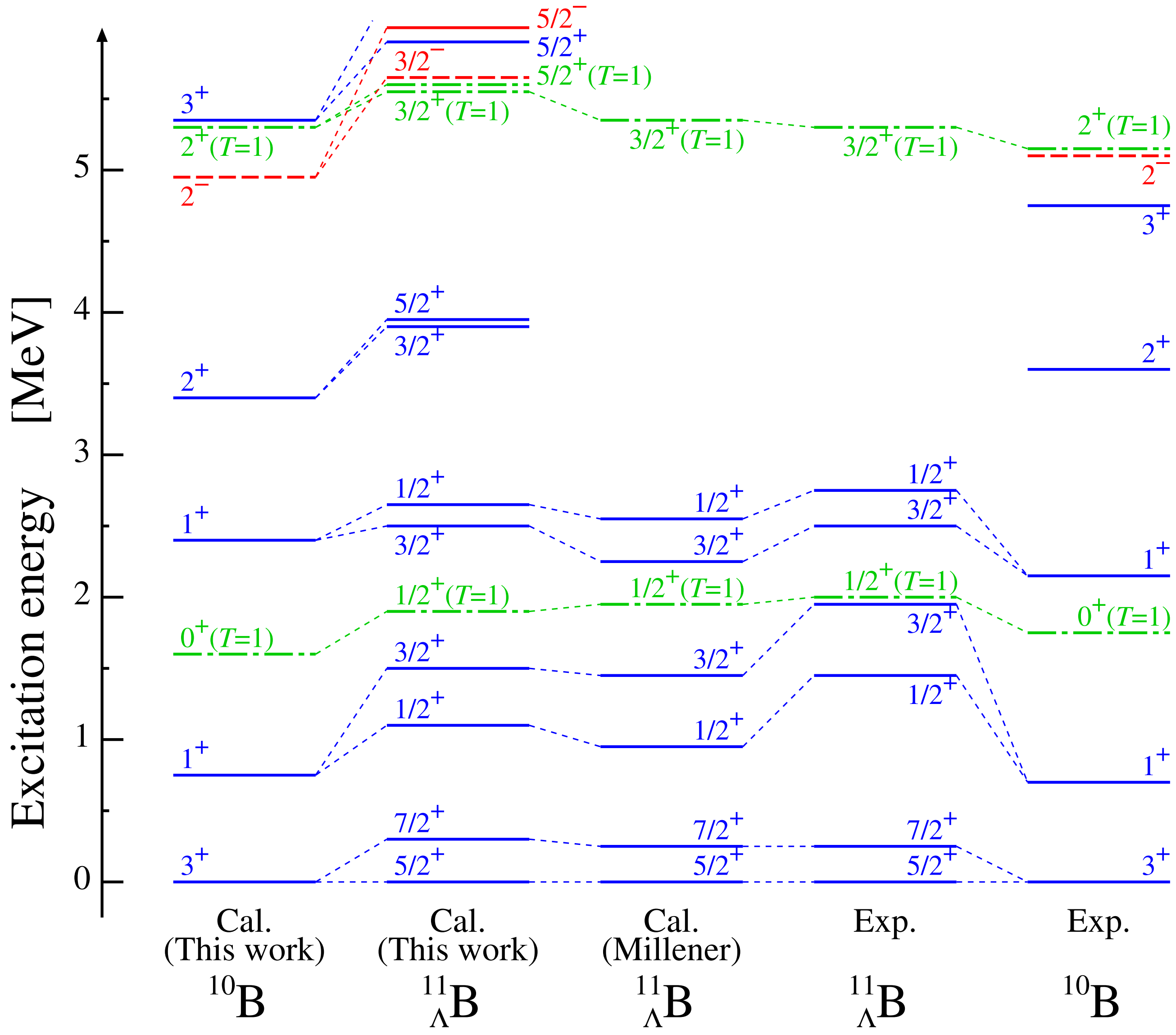
red $T=0, J^-; J^-_{\rm core} \otimes s_\Lambda$

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

green $T=1, J^+; J^+_{\rm core} \otimes s_\Lambda$

brown $T=1, J^-; J^-_{\rm core} \otimes s_\Lambda$

Results : Energy levels of ^{10}B and $^{11}_{\Lambda}$B (2)



3rd and 4th column

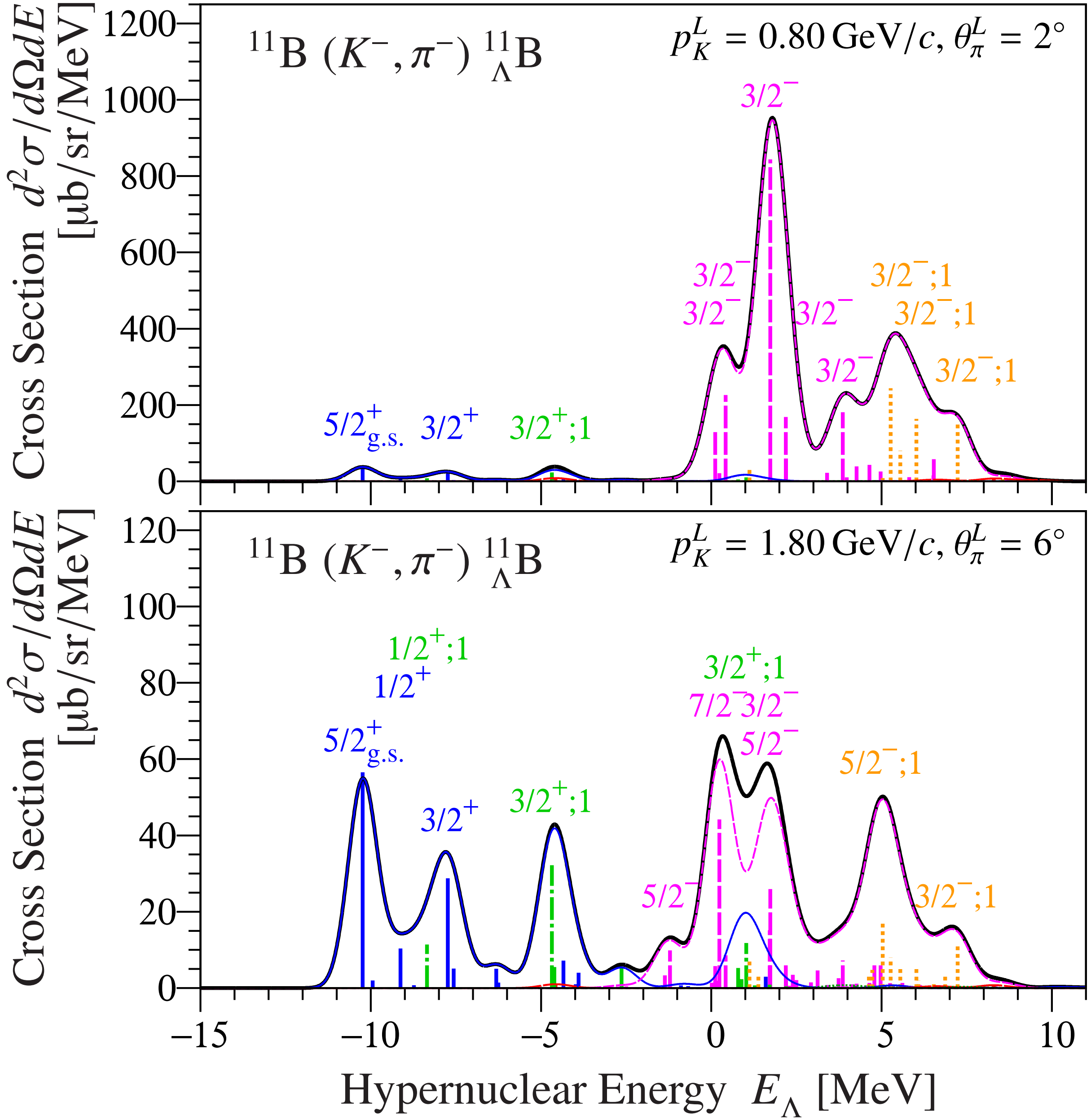
D. J. Millener, NPA804, 84 (2008).

Our result of the energy of the 2nd doublet $(1/2^+, 3/2^+)$ **is almost the same as Millener's result and is** 300 keV **lower than the experimental result.**

For this doublet, effect of the *LS* term of the ΛN **int. is suggested.**

D. J. Millener, NPA804, 84 (2008).

Results : Cross sections of the $^{11}\mathrm{B}\,(K^-,\pi^-)\,^{11}_{\Lambda}\mathrm{B}$ reaction (1)



FWHM = 1.0 MeV

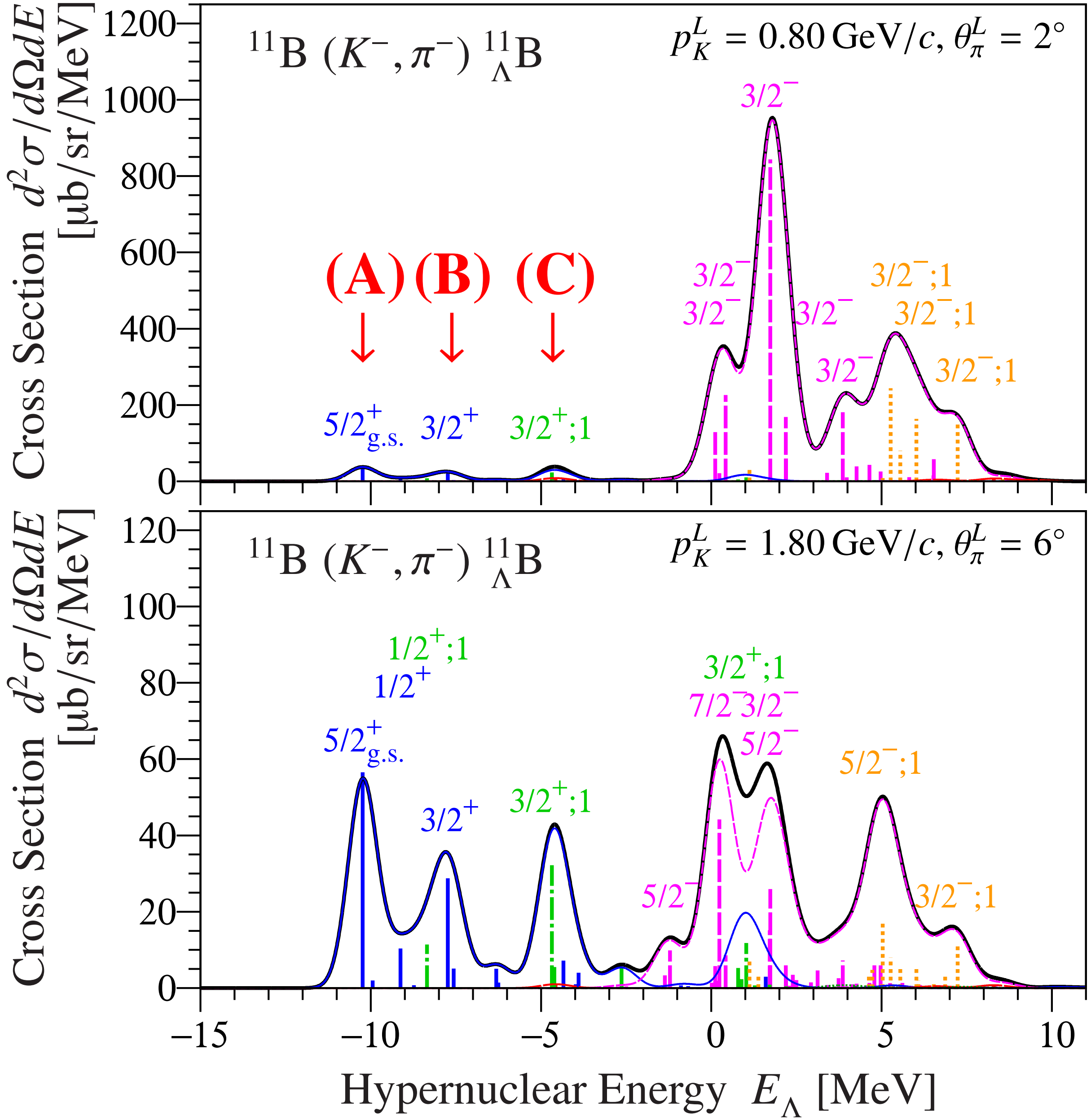
blue $T=0,\ J^+;\ J^+_{\rm core}\otimes s_\Lambda$

green $T=1,\ J^+;\ J^+_{\rm core}\otimes s_\Lambda$

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

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

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



(A) $5/2^+_{\rm g.s.}$

$^{10}\mathrm{B}(3^+_{\rm g.s.})\otimes s^{\Lambda}_{1/2}$ 99.5%

(B) $3/2^+_2$

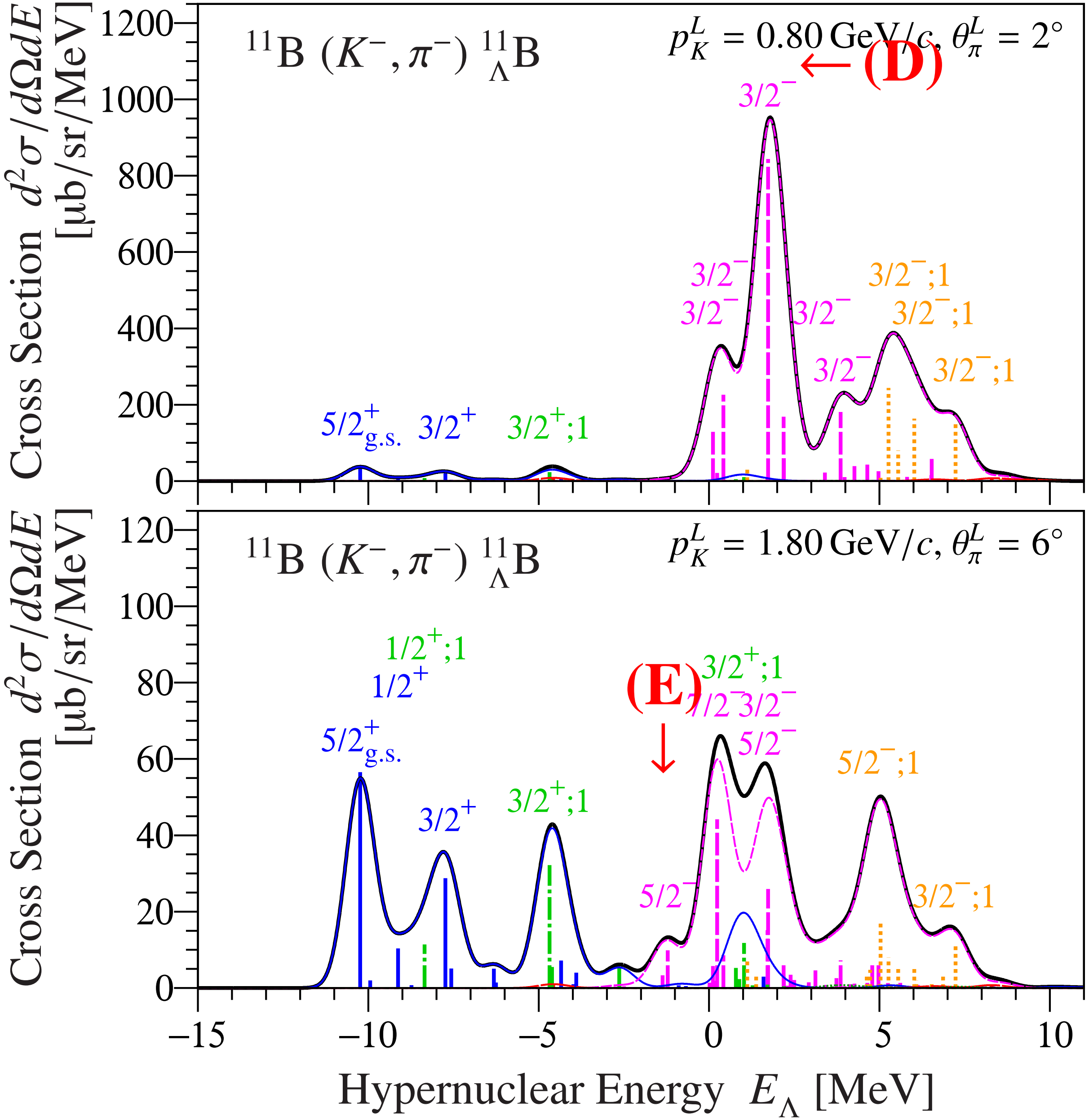
$^{10}\mathrm{B}(1^+_2)\otimes s^{\Lambda}_{1/2}$ 98.0%

(C) $3/2^+_1(T{=}1)$

$^{10}\mathrm{B}(2^+_1;T{=}1)\otimes s^{\Lambda}_{1/2}$ 99.3%

ΛN int. is weak coupling for s^Λ

Results : Cross sections of the $^{11}\mathrm{B}\,(K^-,\pi^-)\,^{11}_{\Lambda}\mathrm{B}$ reaction (3)



(D) $3/2^-$

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

$^{10}\mathrm{B}(1^+_2) \otimes p^{\Lambda}_{1/2}$ 23.0%

$^{10}\mathrm{B}(3^+_2) \otimes p^{\Lambda}_{3/2}$ 9.4%

→ **substitutional state**

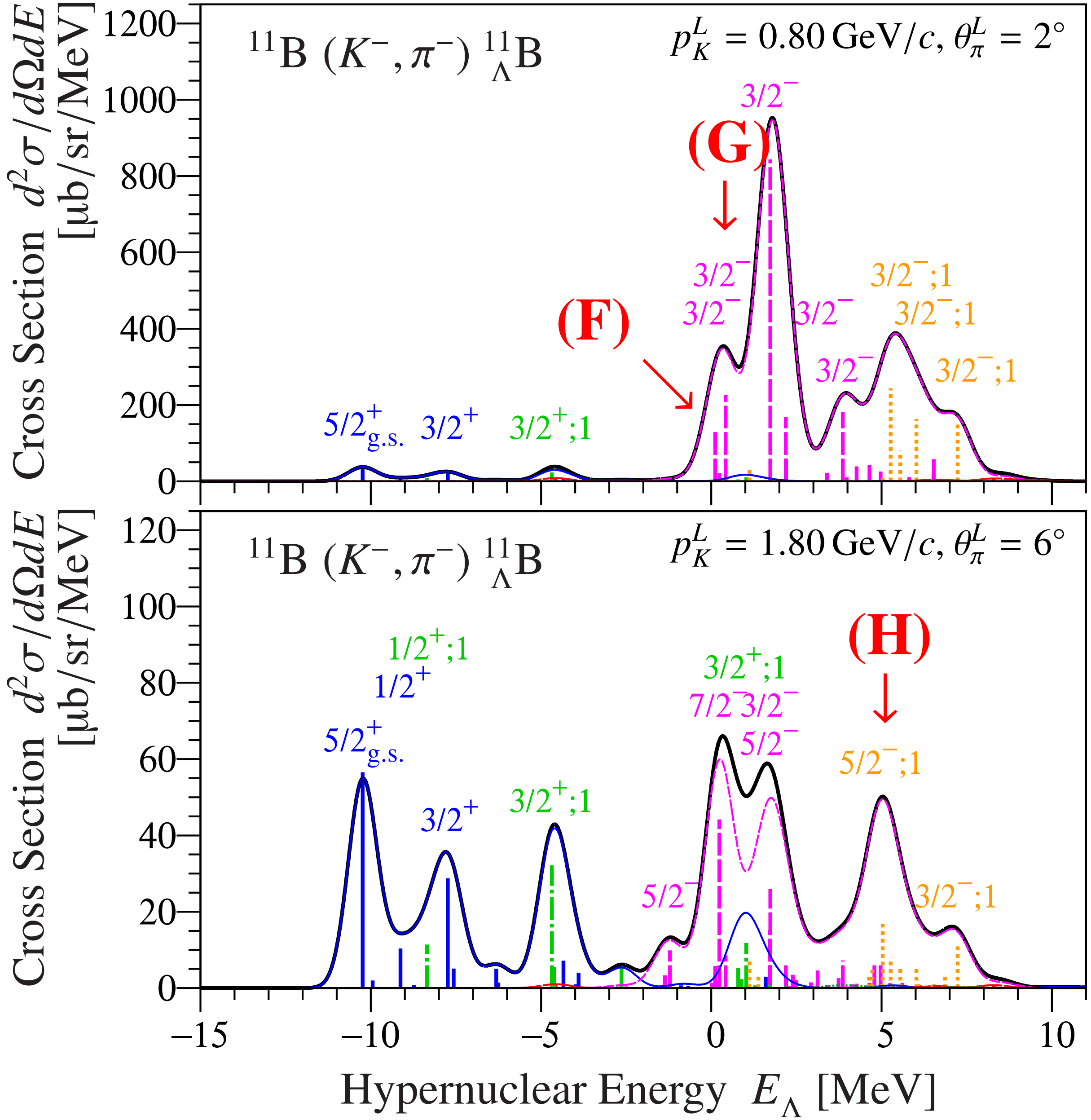
(E) $5/2^-$

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

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

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

Results : Cross sections of the $^{11}\mathrm{B}\,(K^-,\pi^-)\,^{11}_{\Lambda}\mathrm{B}$ reaction (4)



(F) $3/2^-$

$^{10}\mathrm{B}(2^-_3)\otimes s^\Lambda_{1/2}$	58.3%
$^{10}\mathrm{B}(3^+_{\mathrm{g.s.}})\otimes p^\Lambda_{3/2}$	4.2%
$^{10}\mathrm{B}(1^+_1)\otimes p^\Lambda_{3/2}$	9.0%
$^{10}\mathrm{B}(1^+_1)\otimes p^\Lambda_{1/2}$	21.5%

(G) $3/2^-$

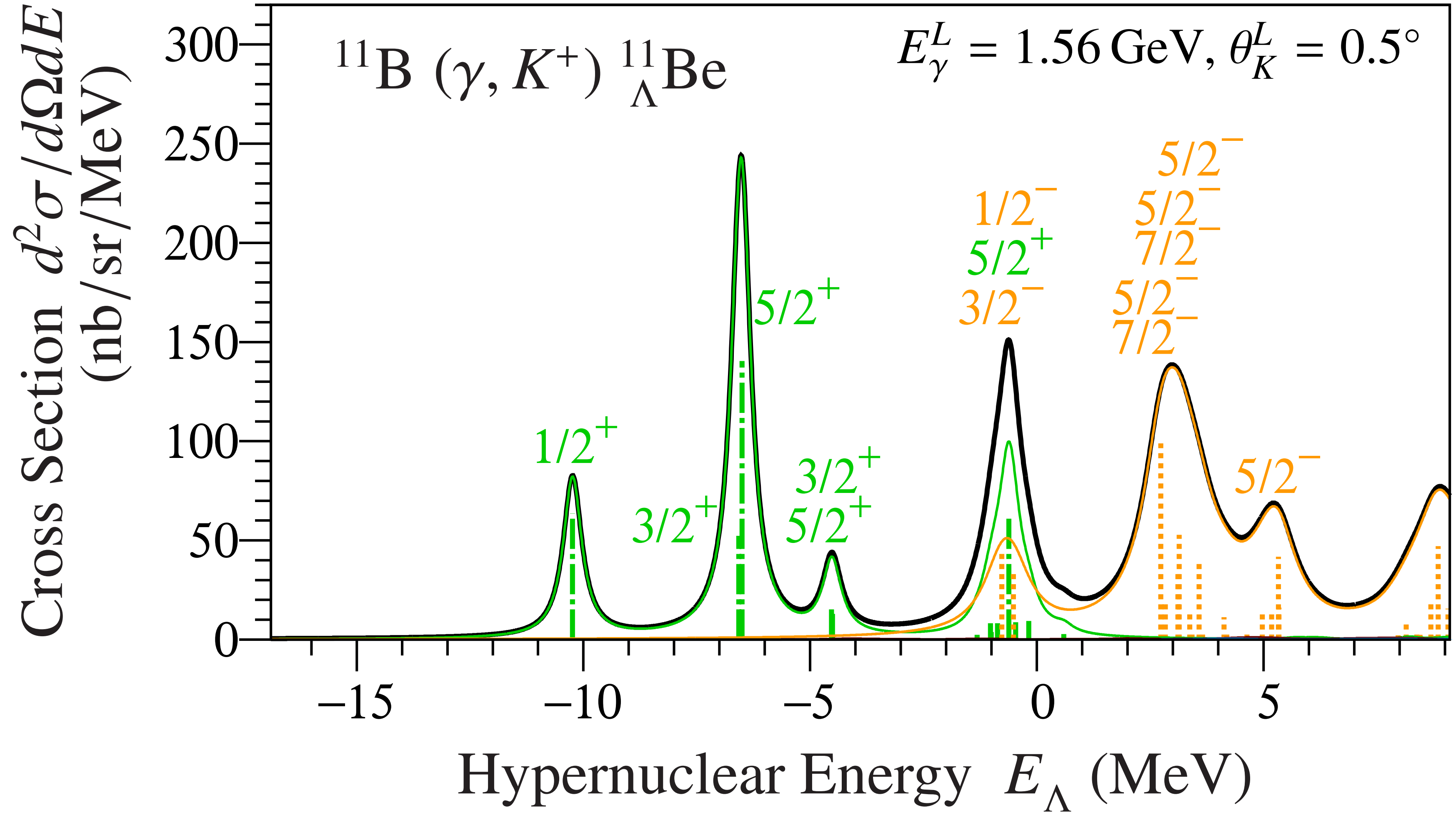
$^{10}\mathrm{B}(2^-_3)\otimes s^\Lambda_{1/2}$	31.6%
$^{10}\mathrm{B}(3^+_{\mathrm{g.s.}})\otimes p^\Lambda_{3/2}$	11.1%
$^{10}\mathrm{B}(1^+_1)\otimes p^\Lambda_{1/2}$	46.9%

(H) $5/2^-(T{=}1)$

$^{10}\mathrm{B}(3^-_3;T{=}1)\otimes s^\Lambda_{1/2}$	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

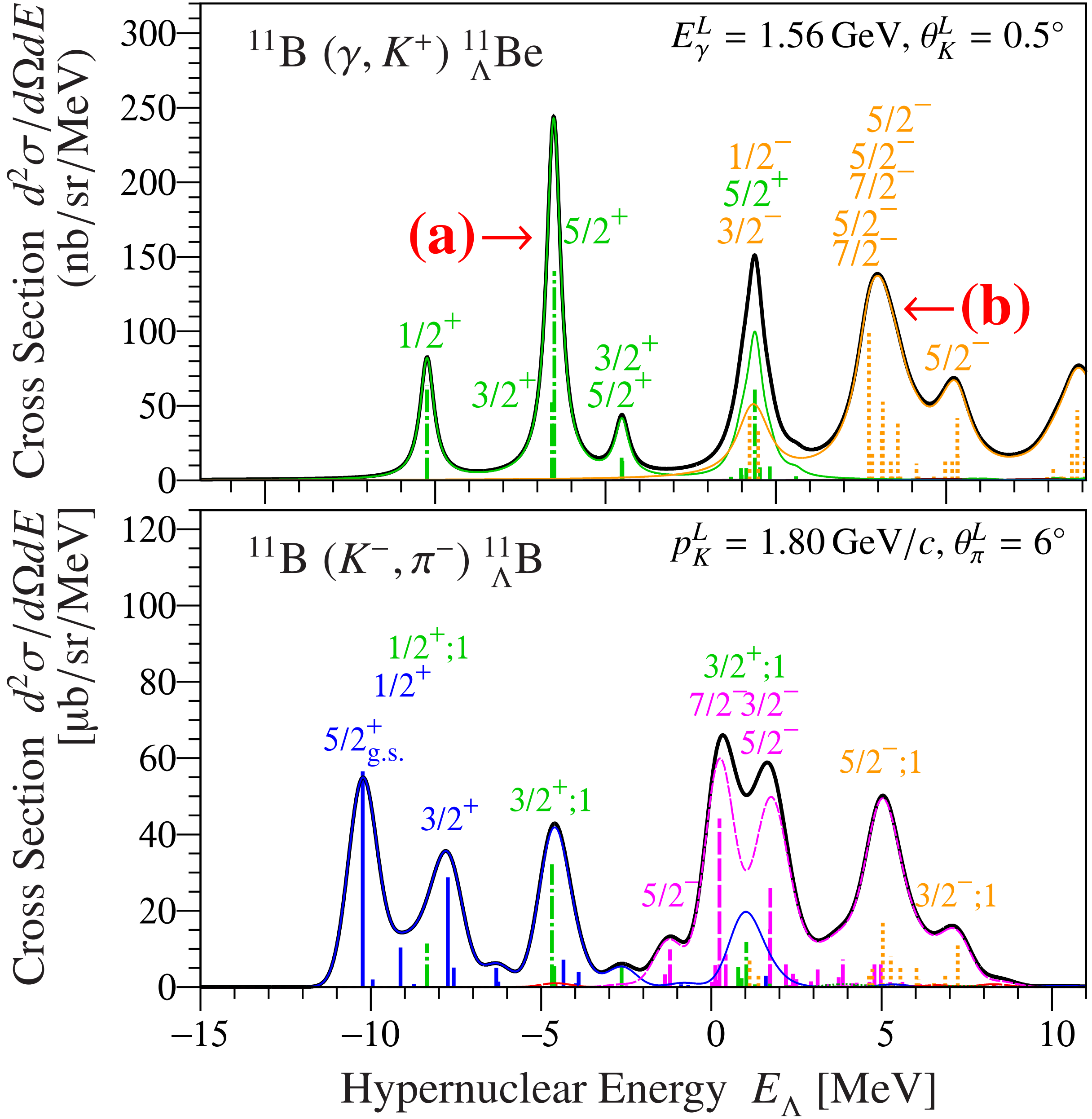
Results : Cross sections of the $^{11}\mathrm{B}\,(\gamma, K^+)\,^{11}_{\Lambda}\mathrm{Be}$ reaction (1)



without QF, FWHM = 1.0 MeV

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

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



(a) $5/2^+(T{=}1)$

$^{10}\mathrm{Be}(2^+_1)\otimes s^{\Lambda}_{1/2}$ 99.5%

(b-1) $5/2^-(T{=}1)$

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

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

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

(b-2) $5/2^-(T{=}1)$

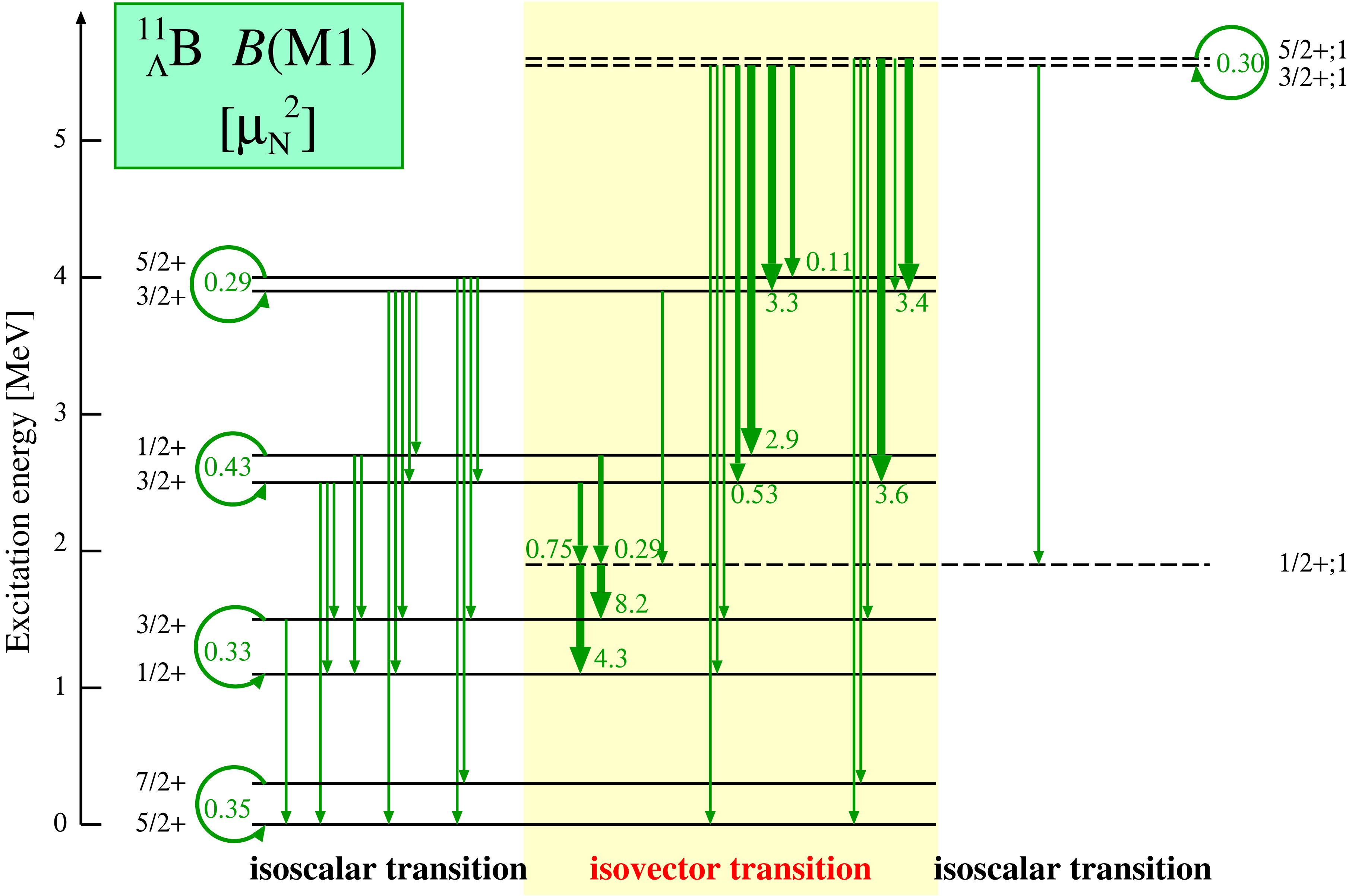
$^{10}\mathrm{Be}(3^-_3)\otimes s^{\Lambda}_{1/2}$ 21.2%

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

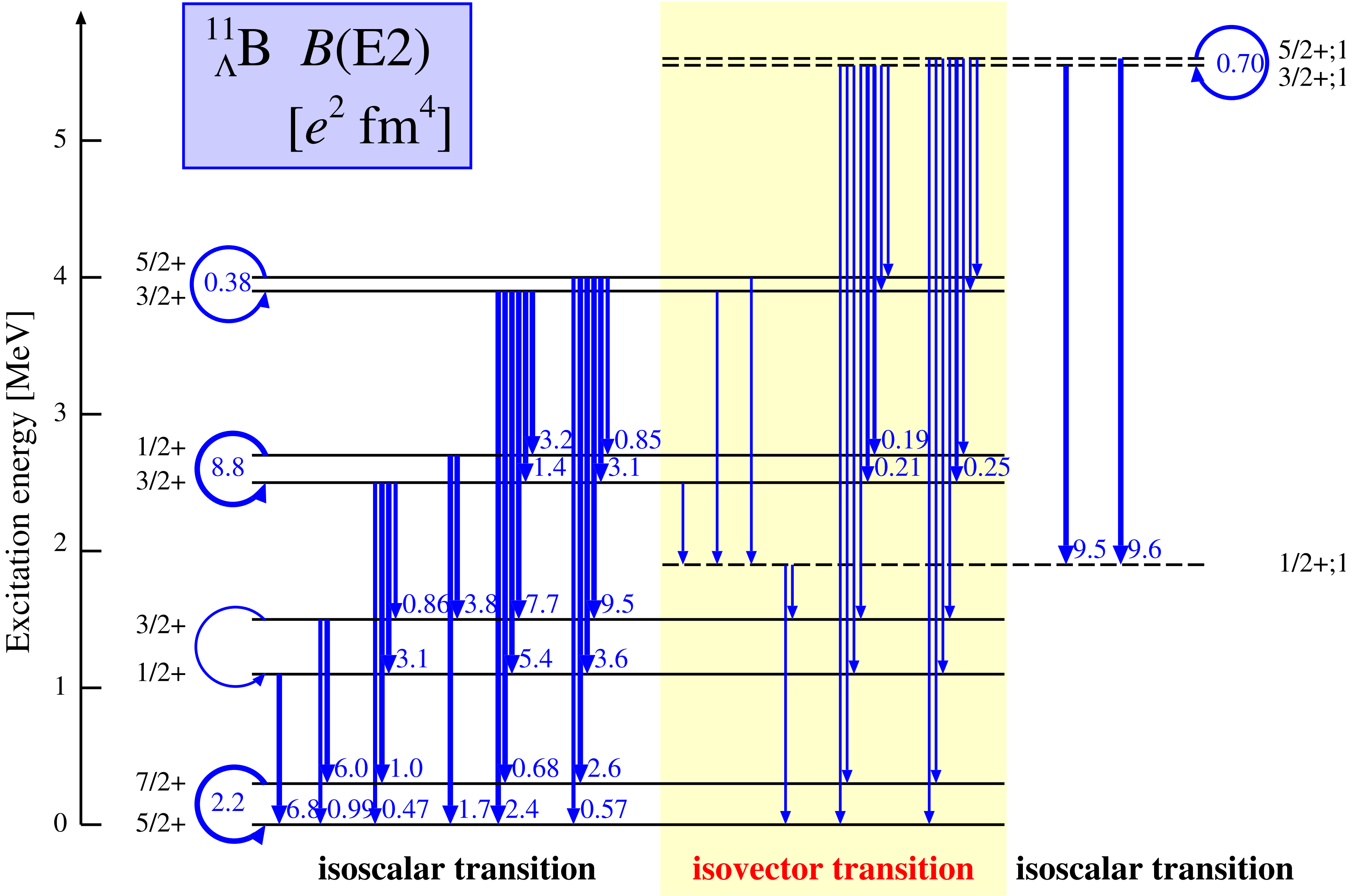
$^{10}\mathrm{Be}(2^+_1)\otimes p^{\Lambda}_{1/2}$ 42.0%

large parity mixing in the core nucleus

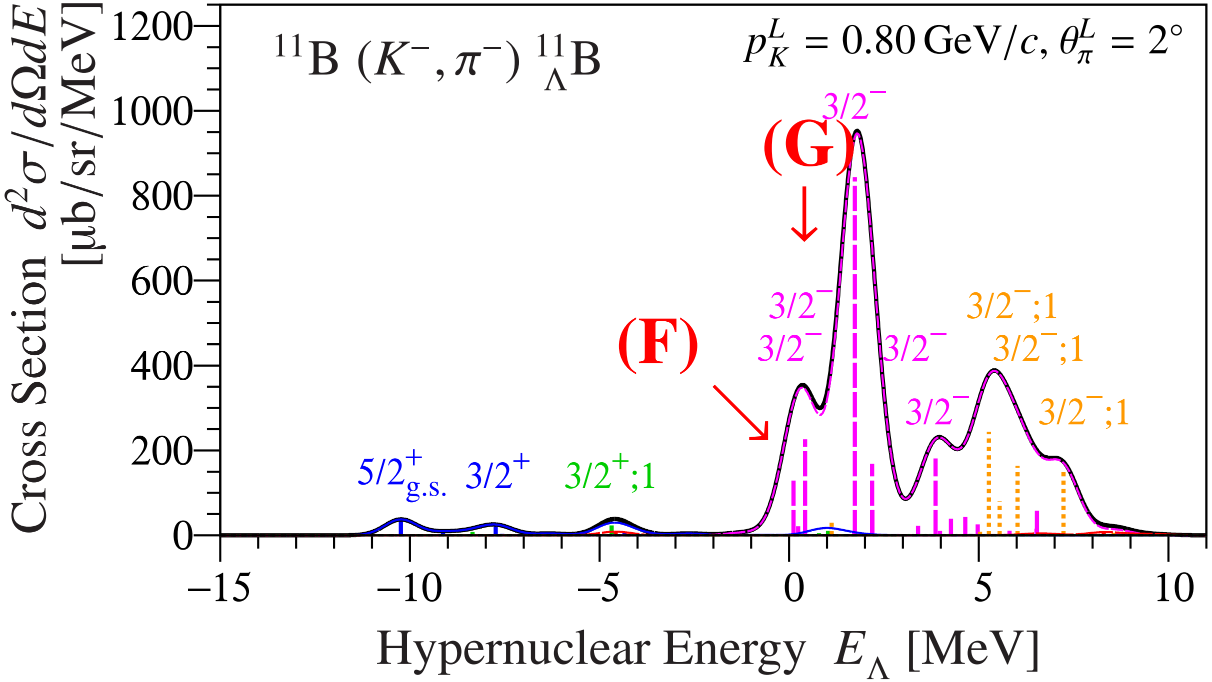
Results : M1 transitions in $^{11}_{\Lambda}$B



Results : E2 transitions in $^{11}_{\Lambda}\mathrm{B}$



Results : E1 transitions from parity-mixing states in $^{11}_{\Lambda}\mathrm{B}$



(F) $3/2^-$

$^{10}\mathrm{B}(2_3^-) \otimes s_{1/2}^{\Lambda}$ 58.3%
$^{10}\mathrm{B}(3_{\mathrm{g.s.}}^+) \otimes p_{3/2}^{\Lambda}$ 4.2%
$^{10}\mathrm{B}(1_1^+) \otimes p_{3/2}^{\Lambda}$ 9.0%
$^{10}\mathrm{B}(1_1^+) \otimes p_{1/2}^{\Lambda}$ 21.5%

(G) $3/2^-$

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

(F) $\rightarrow\ ^{11}_{\Lambda}\mathrm{B}(1/2_1^+)\quad B(\mathrm{E1}) = 0.026\,e\,\mathrm{fm}^2$

(G) $\rightarrow\ ^{11}_{\Lambda}\mathrm{B}(1/2_1^+)\quad B(\mathrm{E1}) = 0.023\,e\,\mathrm{fm}^2$

(with $e_\Lambda^{\mathrm{eff}} = -Ze/A$)

dominant component $^{10}\mathrm{B}(1_1^+) \otimes p_{1/2}^{\Lambda} \xrightarrow{\mathrm{E1}} {}^{10}\mathrm{B}(1_1^+) \otimes s_{1/2}^{\Lambda}$

$^{10}\mathrm{B}(1_1^+) \otimes p_{1/2}^{\Lambda}$ splits into states (F) and (G) due to the parity-mixing by ΛN interaction

Summary

We have calculated the energy levels the cross sections of the (K^-, π^-) and (γ, K^+) reactions, and the electromagnetic transition strengths for the ${}^{11}_{\Lambda}\mathrm{B}$ (${}^{11}_{\Lambda}\mathrm{Be}$) hypernucleus by using the extended shell model.

Extension (1) 1*p*-1*h* (1$\hbar\omega$) core excitation is taken into account

Extension (2) Configrations mixed by Λ*N* interaction

$$\boxed{J^-_{\mathrm{core}} \otimes 0s^{\Lambda}} \oplus \boxed{J^+_{\mathrm{core}} \otimes 0p^{\Lambda}} \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}(J^-)$$

$$\boxed{J^-_{\mathrm{core}} \otimes 0p^{\Lambda}} \oplus \boxed{J^+_{\mathrm{core}} \otimes 0s^{\Lambda}} \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}(J^+)$$

- **Our result of the energy of the 2nd doublet** $(1/2^+, 3/2^+)$ **is** 300 keV **lower than the experimental result.**
- **For the** (K^-, π^-) **and** (γ, K^+) **reactions, the DWIA calculation shows the large cross sections of unnatural-parity states with intershell mixing of the nuclear core-excited states having different parities.**
- **The parity-mixing can affect E1 transition strengths.**