Baryon Interaction Study from Hypernuclear reaction and structure via electrO-Production method 2023
(BISHOP2023)

May 17, 2023

Structures of ${}^{11}_{\Lambda}\mathrm{Be}$ and ${}^{27}_{\Lambda}\mathrm{Mg}$ hypernuclei and estimates of photoproduction cross sections

Atsushi UMEYA (Nippon Inst. of Tech.)

collaborated with

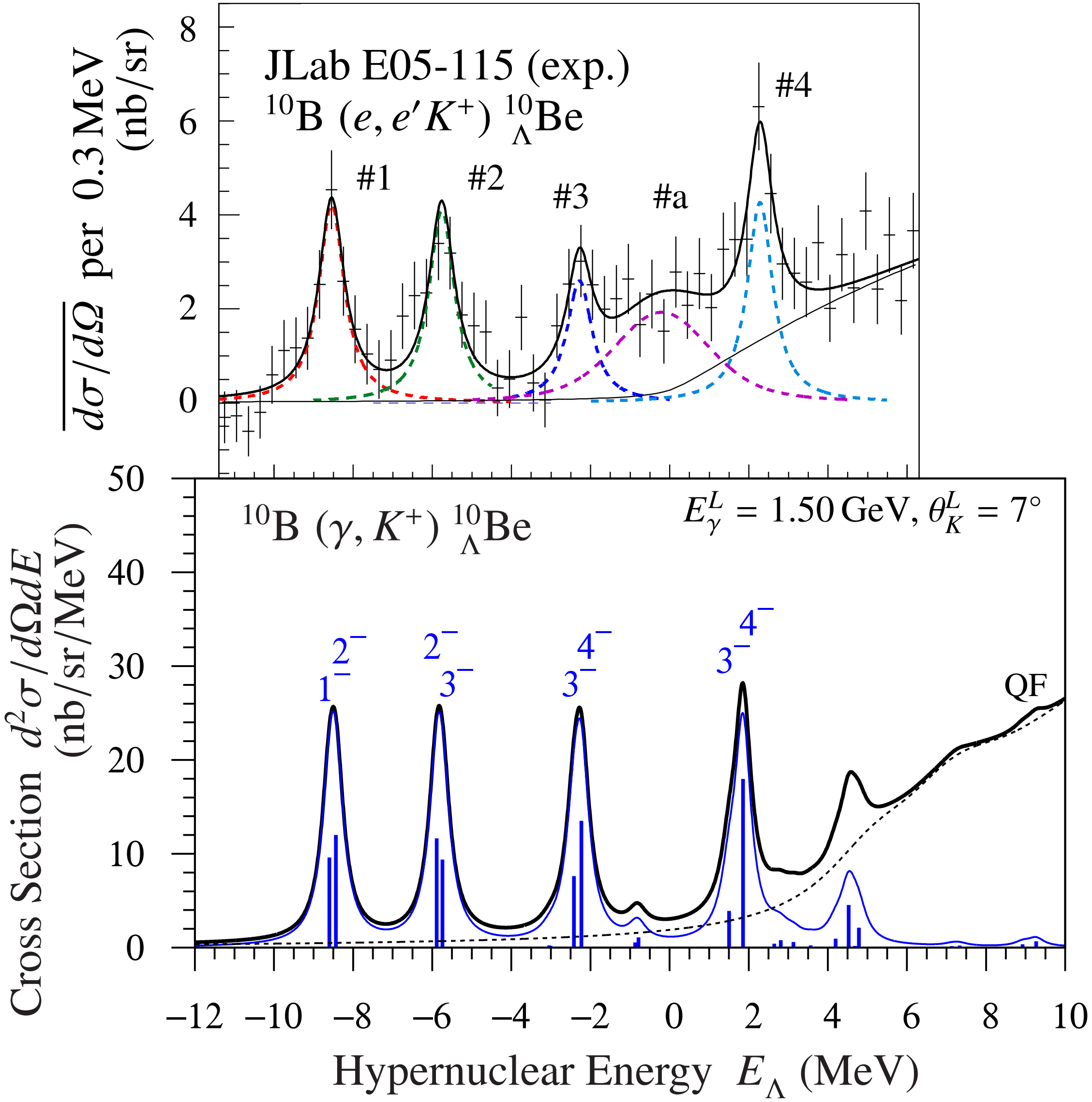
Toshio MOTOBA (RCNP, Osaka Univ. / Osaka E-C Univ.)

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.**
- **The level structures of sd-shell nuclei are richer and more complex than those of p-shell nuclei. It is interesting to see effects of hyperon addition for these core nuclei.**
- **High-precision experiments in hypernuclear spectroscopy are in progress.**
- **We focus on the p-state Λ hyperon in the p-shell Λ hypernucleus ${}^{11}_{\Lambda}$Be and the sd-shell Λ hypernucleus ${}^{27}_{\Lambda}$Mg, which can be produced by $(e, e'K^+)$ reactions.**

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



Recent experimental result

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

Shell-model prediction

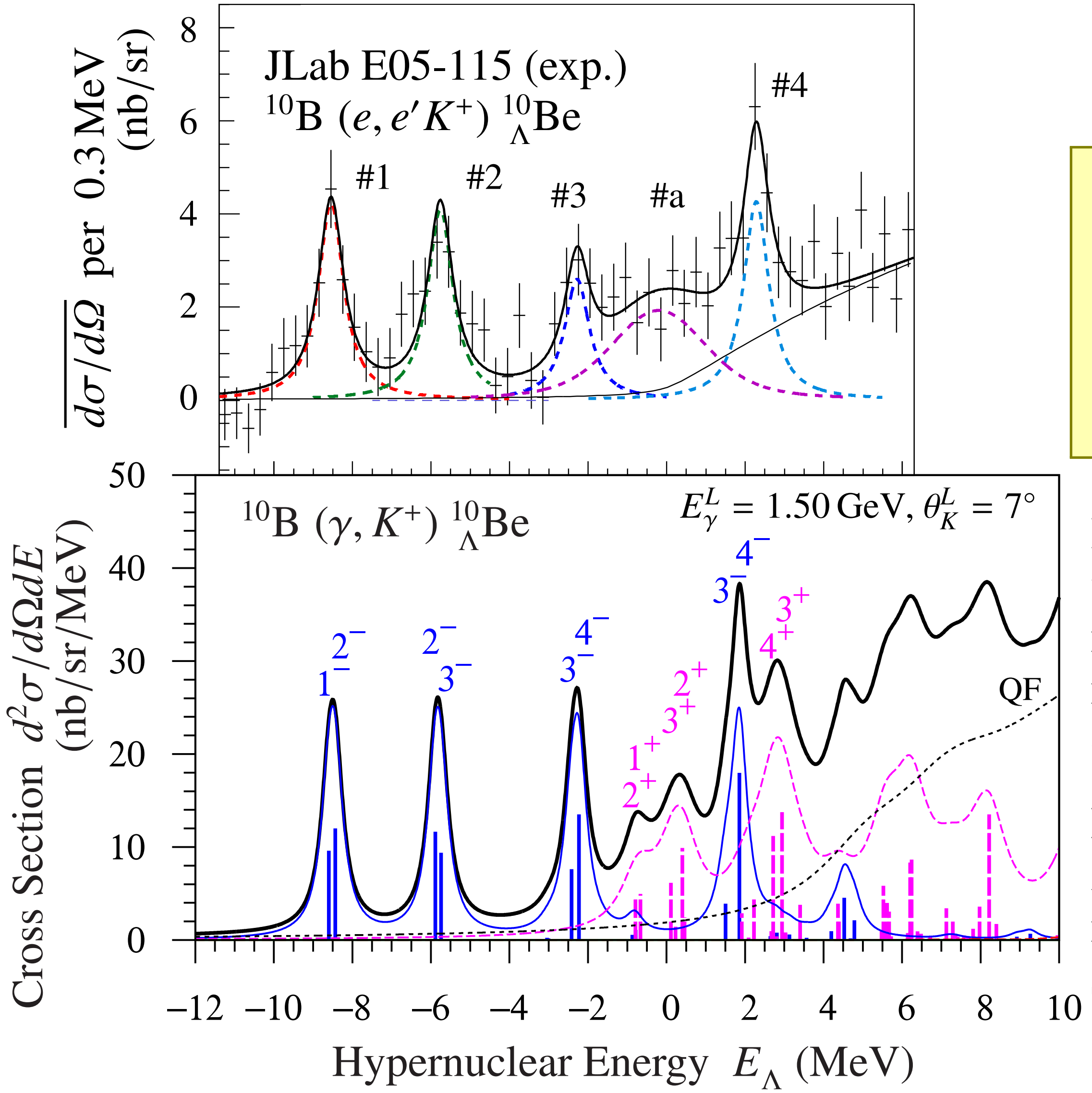
T. Motoba *et al.*, PTPS117, 123 (1994)

- **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.

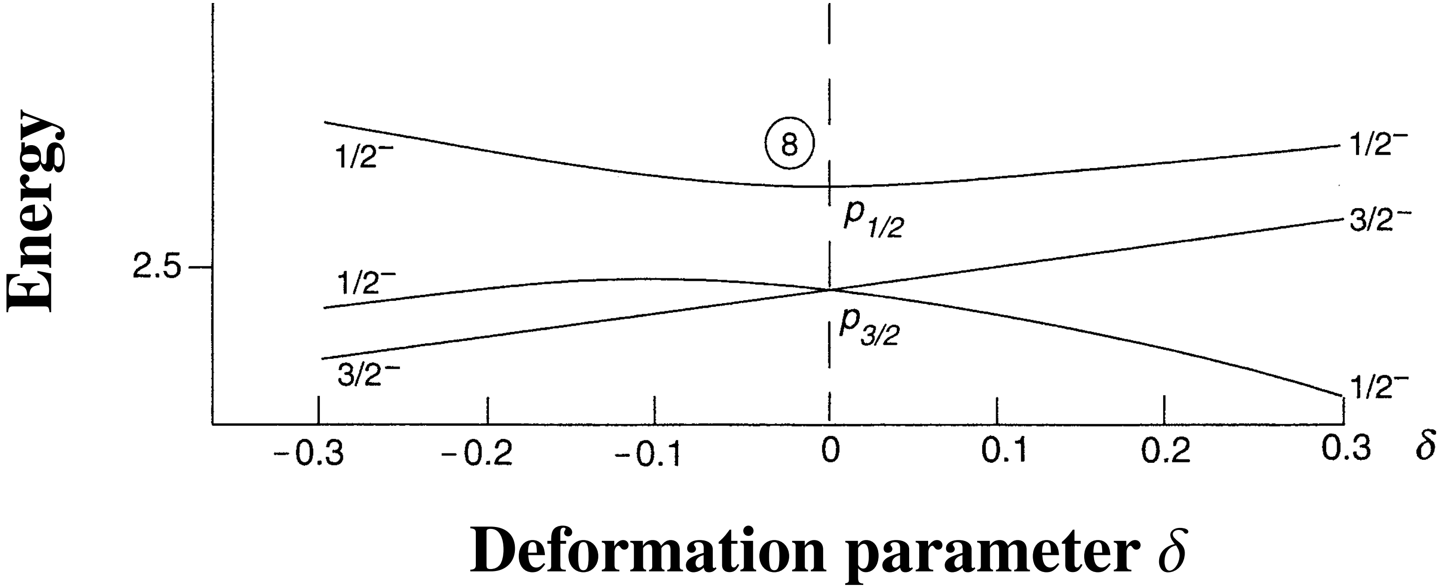
are taken into account

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.

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.

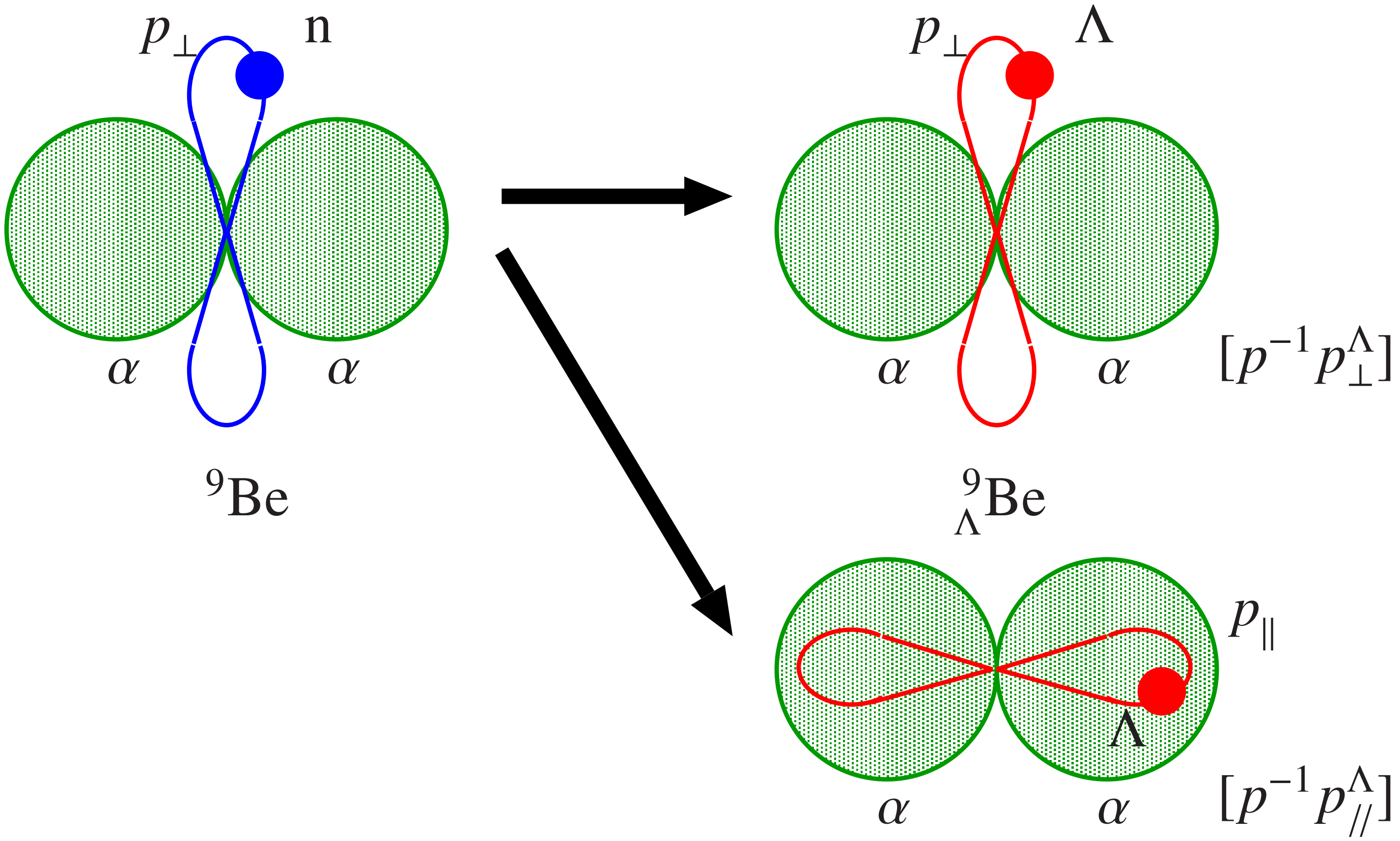


S. G. Nilsson, Mat. Fis. Medd. Dan. Vid. Selsk. 29 (1955) No. 16

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

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

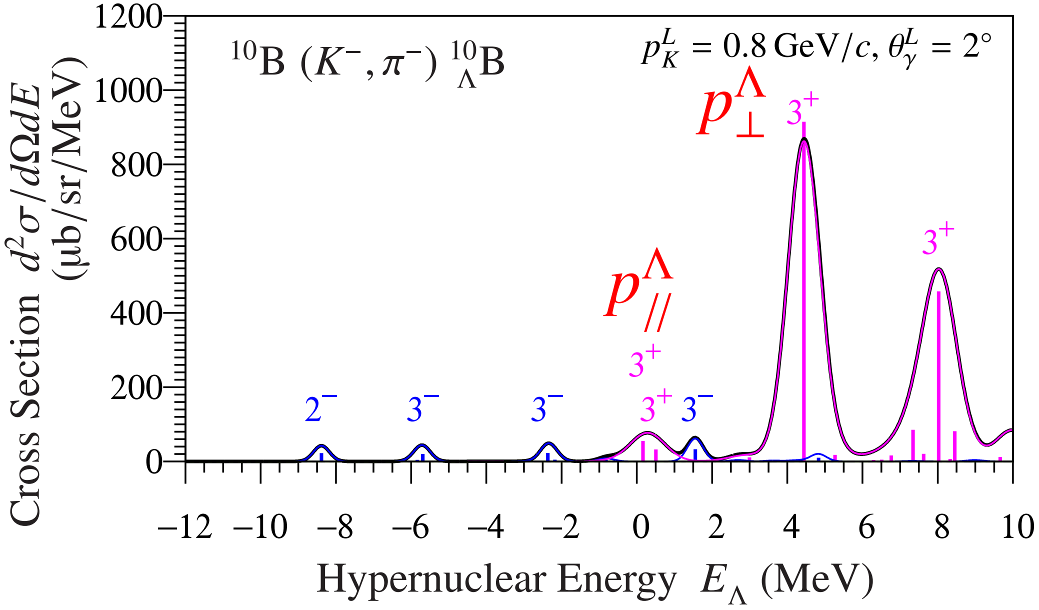
$p_\perp^\Lambda$ and $p_{//}^\Lambda$ states of ${}^{9}_{\Lambda}\mathrm{Be}$

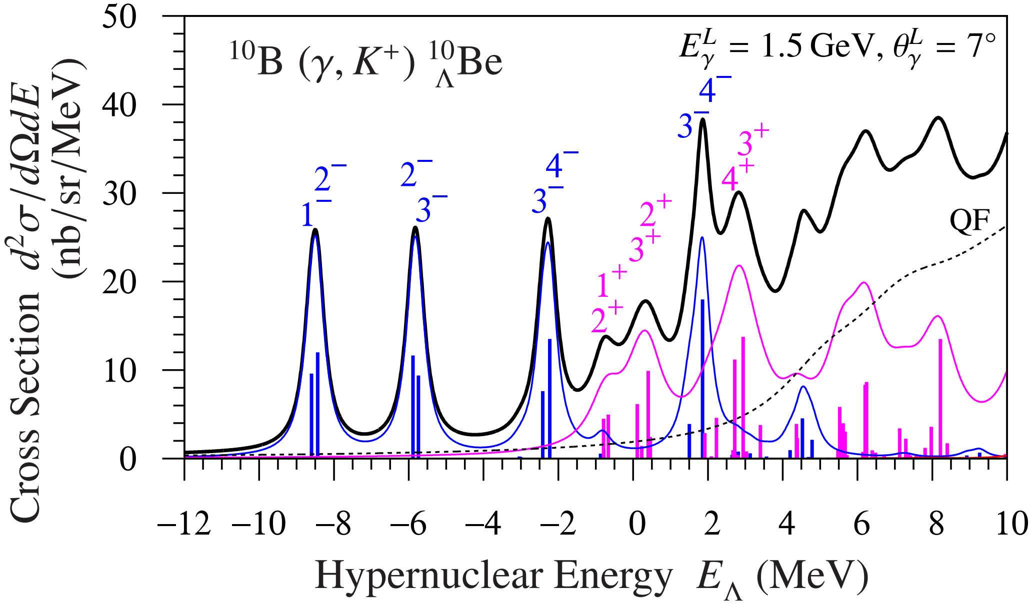


In ${}^{9}_{\Lambda}\mathrm{Be}$, it is well known that the p_Λ-state splits into two orbital states expressed by $p_\perp$ and $p_{//}$, which is due to the strong coupling with nuclear core deformation having the α-α structure.

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

$p_{\perp}^{\Lambda}$ and $p_{//}^{\Lambda}$ states of ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B (1)





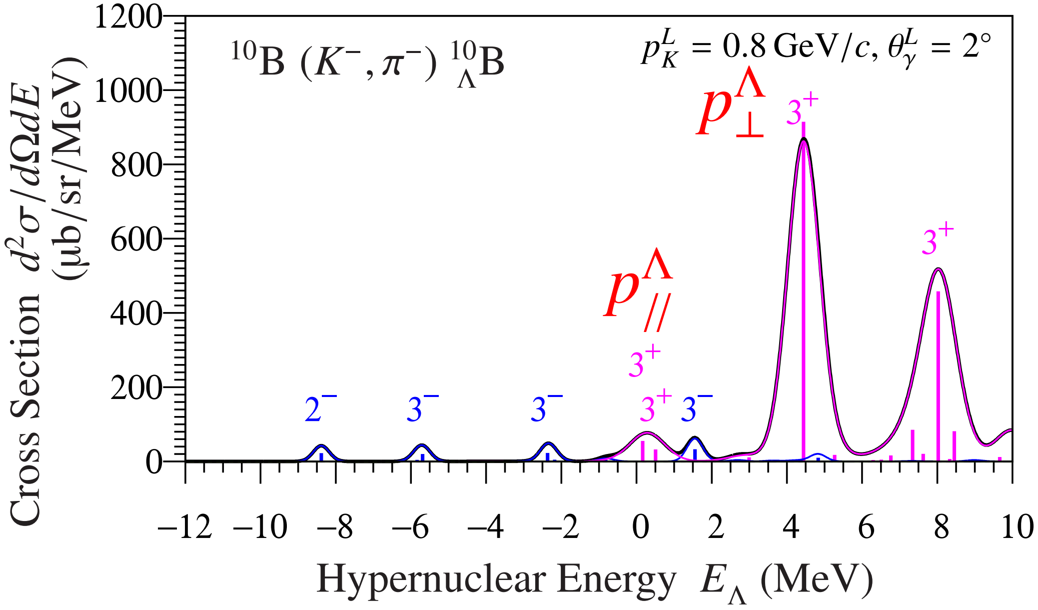
In the (K^-, π^-) reaction, the large peak at $E_\Lambda = 4.4$ MeV is a p-substitutional state via the $p^N_{3/2} \to p^\Lambda_{3/2}$, which is strongly excited by recoilless reaction.

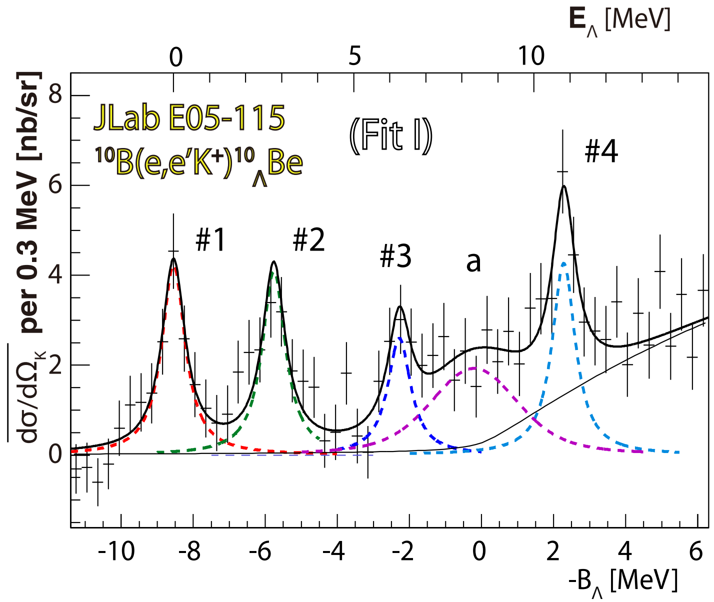
The small peak at $E_\Lambda = 0$ MeV corresponds to the new bump and is explained as a mixture of s^Λ and p^Λ states.

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

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

$p_{\perp}^{\Lambda}$ and $p_{//}^{\Lambda}$ states of ${}^{10}_{\Lambda}\mathrm{Be}$ and ${}^{10}_{\Lambda}\mathrm{B}$ (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 $E_\Lambda = 0\,\mathrm{MeV}$ can explain the extra peak #a.

This talk

- **We focus on the p-state Λ hyperon in the p-shell Λ hypernucleus ${}^{11}_{\Lambda}$Be and the sd-shell Λ hypernucleus ${}^{27}_{\Lambda}$Mg, which can be produced by $(e, e'K^{+})$ reactions.**

$$\mathbf{{}^{11}B\ (e, e'K^{+})\ {}^{11}_{\Lambda}Be, \qquad {}^{27}Al\ (e, e'K^{+})\ {}^{27}_{\Lambda}Mg}$$

- **^{10}Be and ^{26}Mg are even-even core nuclei with the isospin $T = 1$.**

- **We will show the results of new calculations for an sd-shell hypernuclear structure of ${}^{27}_{\Lambda}$Mg, in which the core nucleus ^{26}Mg is shown to have rotational bands. Thus we see coupling of the p_{Λ} orbital and the core deformation.**

Model space for p- and sd-shell hypernuclei

In the extended model we have proposed recently for p-shell hypernuclei, each hypernuclear state of $J^{\pm}$ is described by taking four types of configurations,

$$[J^{+}_{\rm core} \otimes \Lambda(0s)]_{J^{+}},\ [J^{+}_{\rm core} \otimes \Lambda(0p)]_{J^{-}},\ [J^{-}_{\rm core} \otimes \Lambda(0s)]_{J^{-}},\ [J^{-}_{\rm core} \otimes \Lambda(0p)]_{J^{+}}.$$

(e.g.) For ${}^{10}_{\Lambda}$Be, $[J^{+}_{\rm core} \otimes \Lambda(0p)]_{J^{-}}$ and $[J^{-}_{\rm core} \otimes \Lambda(0s)]_{J^{-}}$ can be mixed easily by the ΛN interaction at appropriate excitation energy.

We applied this extended model to sd-shell hypernuclei.

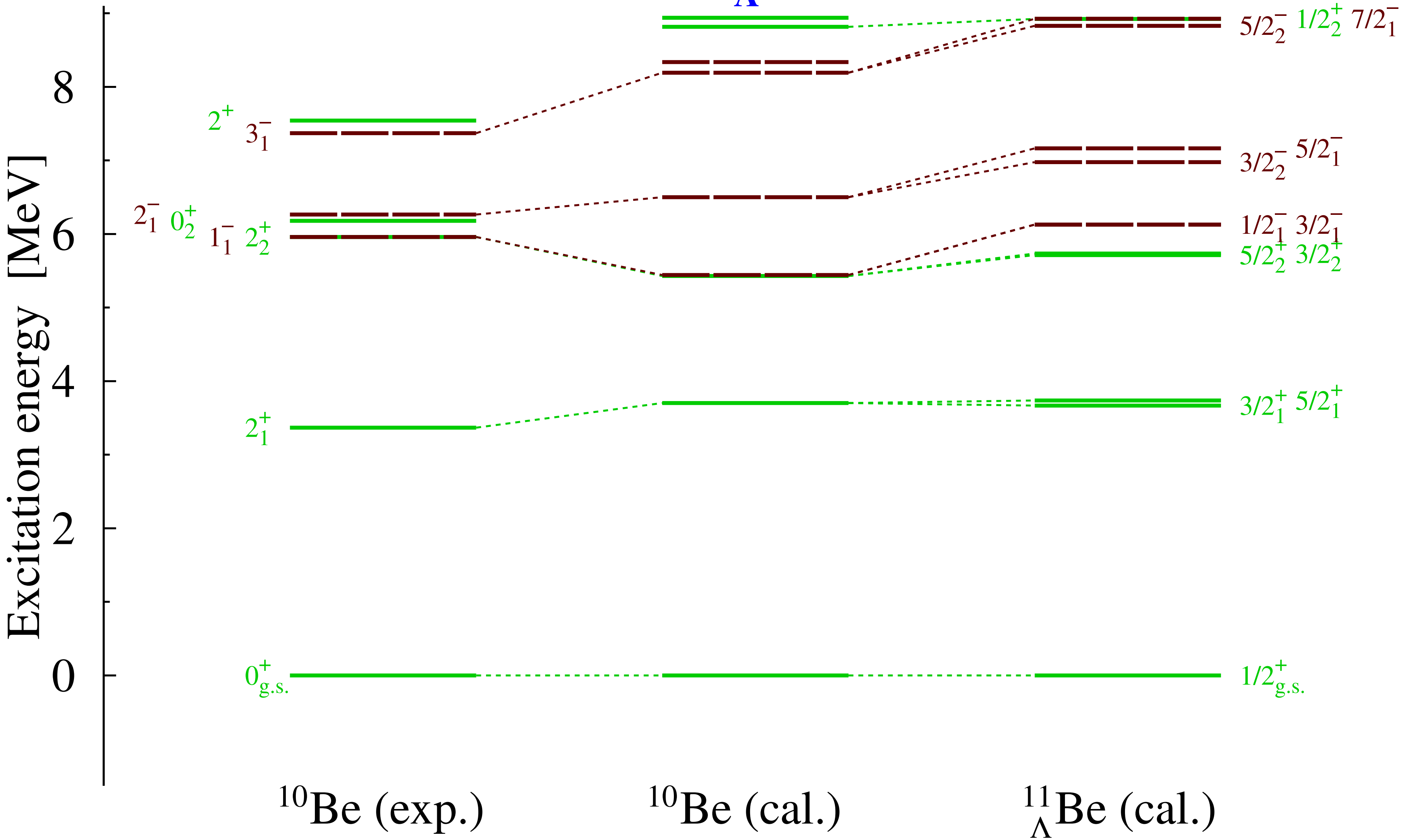
Core nucleus ^{26}Mg, ^{26}Al $J^{+}_{\rm core}\ (0\hbar\omega) = ({}^{16}{\rm O})(sd)^{10}$, $J^{-}_{\rm core}\ (1\hbar\omega) = ({}^{16}{\rm O})(0p)^{-1}(sd)^{11}$

Λ hyperon $0s(0\hbar\omega)$, $0p(1\hbar\omega)$, $sd(2\hbar\omega)$

6 type configurations for ${}^{27}_{\Lambda}{\rm Mg}(J)$ and ${}^{27}_{\Lambda}{\rm Al}(J)$,

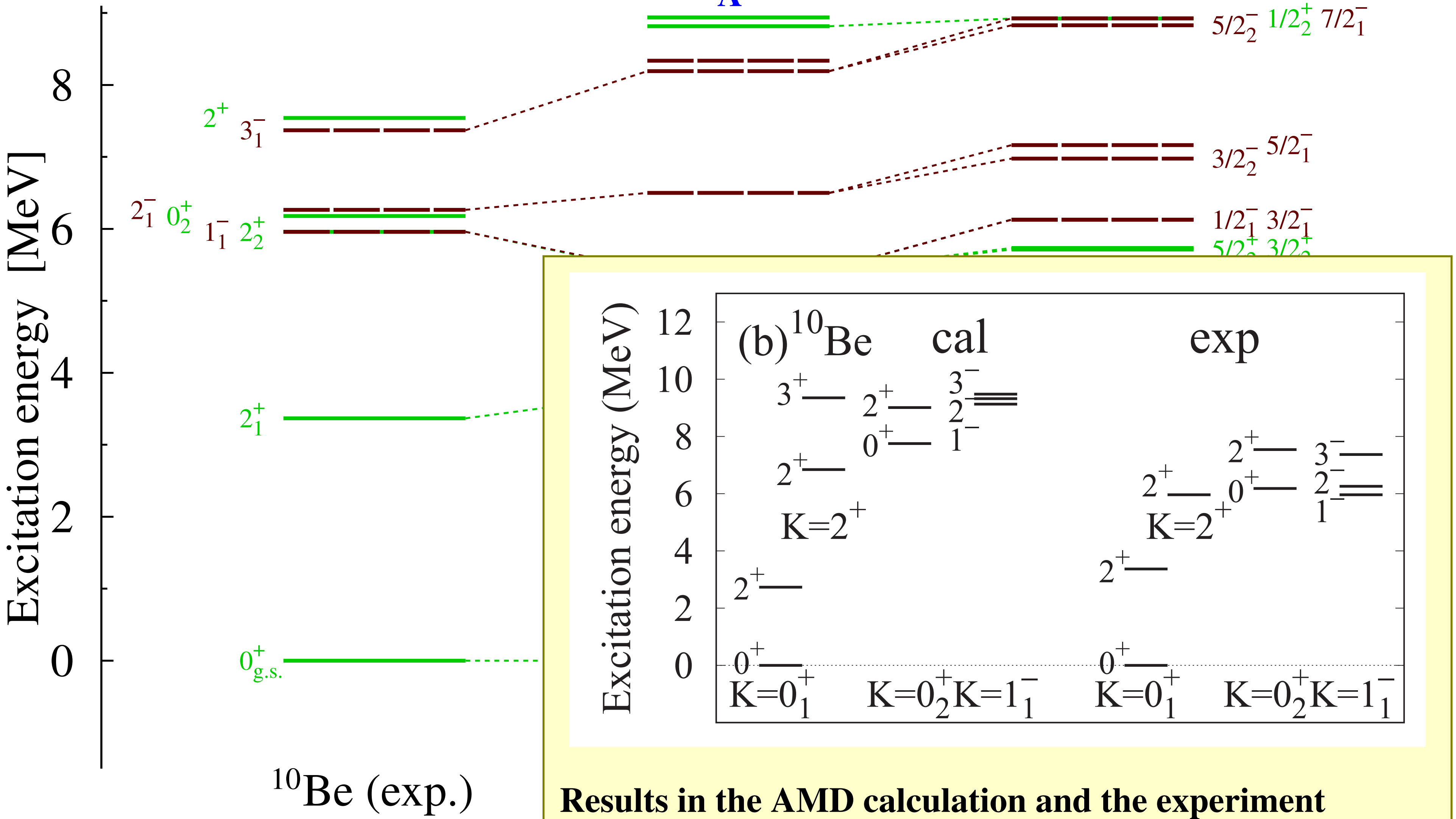
$$\begin{array}{ll}
J^{+}_{\rm core} \otimes \Lambda(0s) \rightarrow J^{+}\ (0\hbar\omega) & J^{-}_{\rm core} \otimes \Lambda(0s) \rightarrow J^{-}\ (1\hbar\omega) \\
J^{+}_{\rm core} \otimes \Lambda(0p) \rightarrow J^{-}\ (1\hbar\omega) & J^{-}_{\rm core} \otimes \Lambda(0p) \rightarrow J^{+}\ (2\hbar\omega) \\
J^{+}_{\rm core} \otimes \Lambda(sd) \rightarrow J^{+}\ (2\hbar\omega) & J^{-}_{\rm core} \otimes \Lambda(sd) \rightarrow J^{-}\ (3\hbar\omega)
\end{array}$$

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



dominant configurations **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}Be and $^{11}_{\Lambda}$Be (2)

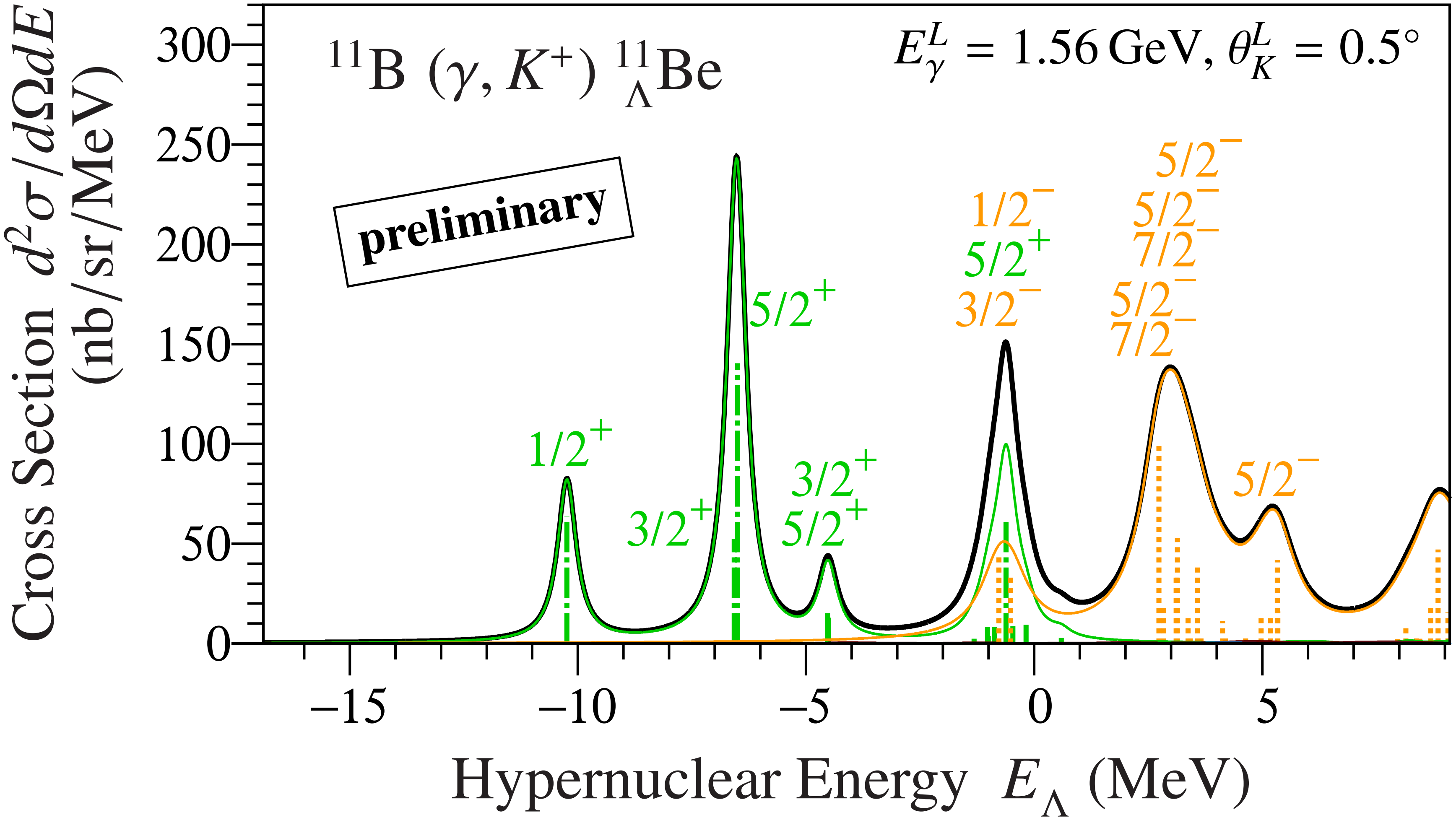


Results in the AMD calculation and the experiment

Y. Kanada-En'yo, Y. Shikata, Y. Chiba, K. Ogata,
Phys. Rev. C 102, 014607 (2020)

dominant configurations green T=1,

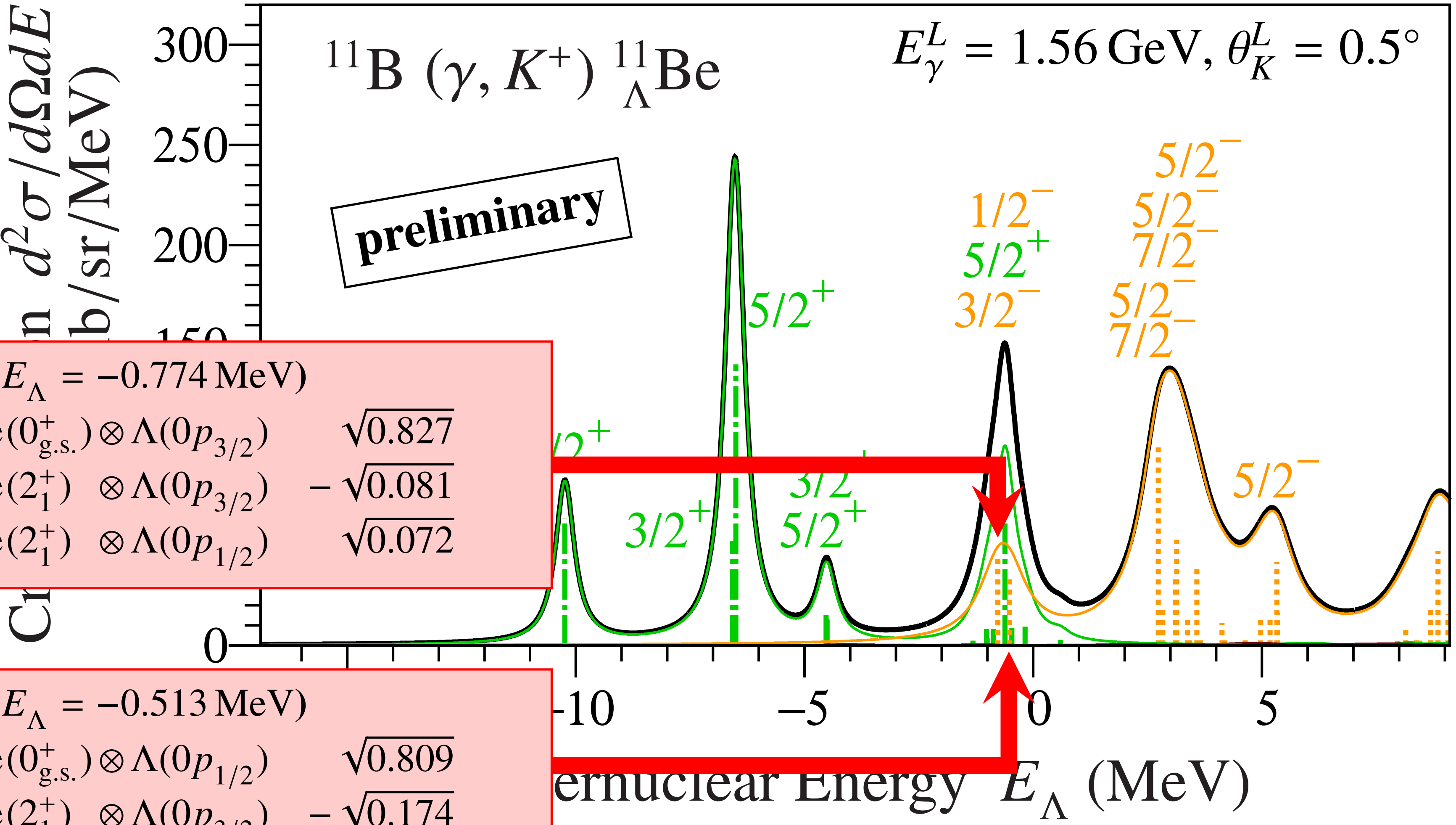
Results : Cross sections of the $^{11}\mathrm{B}\,(\gamma, K^+)\,^{11}_{\Lambda}\mathrm{Be}$ reaction (1)



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)



$3/2^-\ (E_\Lambda = -0.774\,\mathrm{MeV})$

$^{10}\mathrm{Be}(0^+_{\mathrm{g.s.}}) \otimes \Lambda(0p_{3/2})\quad \sqrt{0.827}$

$^{10}\mathrm{Be}(2^+_1) \otimes \Lambda(0p_{3/2})\quad -\sqrt{0.081}$

$^{10}\mathrm{Be}(2^+_1) \otimes \Lambda(0p_{1/2})\quad \sqrt{0.072}$

$1/2^-\ (E_\Lambda = -0.513\,\mathrm{MeV})$

$^{10}\mathrm{Be}(0^+_{\mathrm{g.s.}}) \otimes \Lambda(0p_{1/2})\quad \sqrt{0.809}$

$^{10}\mathrm{Be}(2^+_1) \otimes \Lambda(0p_{3/2})\quad -\sqrt{0.174}$

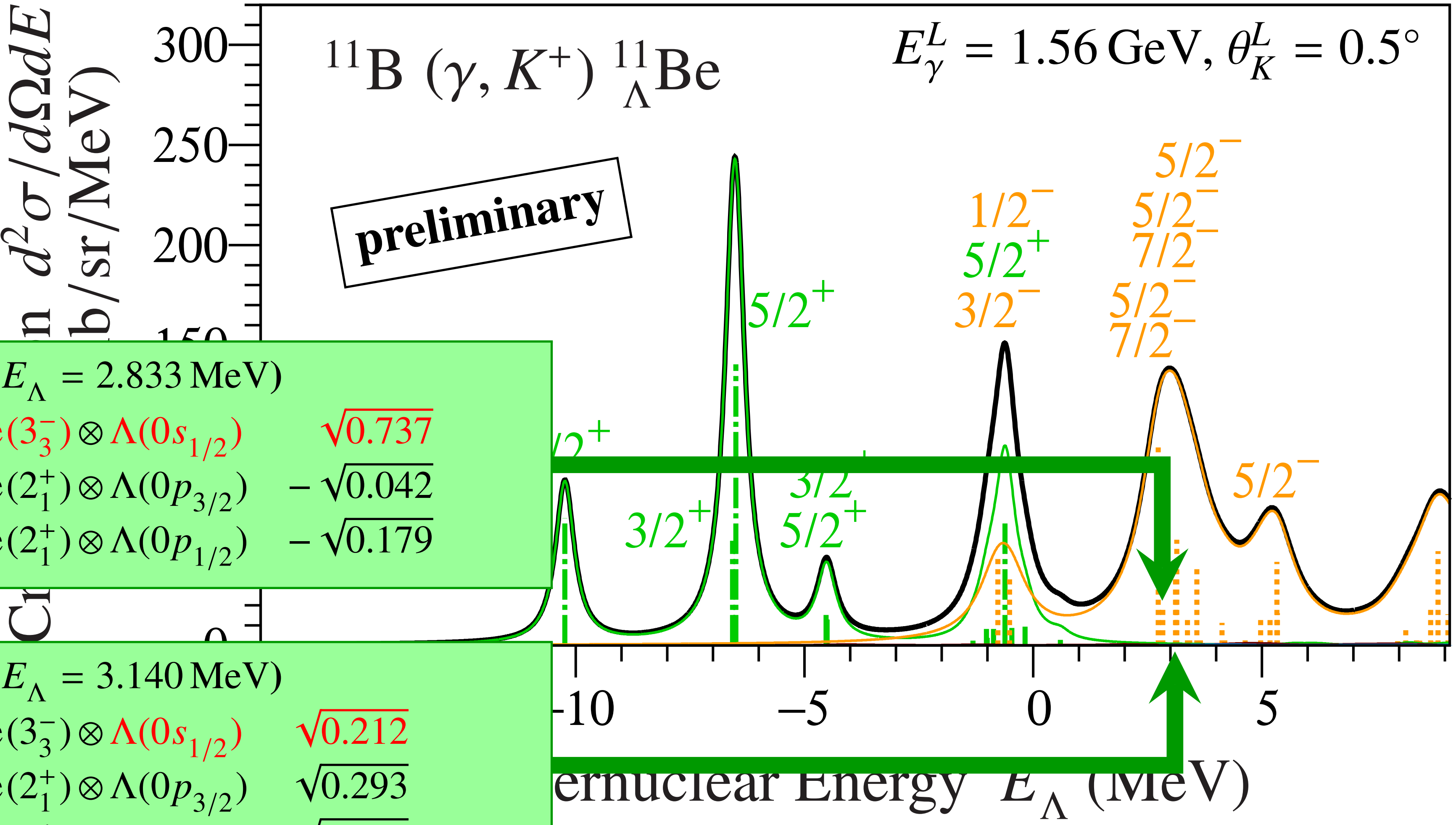
without QF, FWHM = 1.0 MeV

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 (3)



$5/2^-$ ($E_\Lambda = 2.833\,\mathrm{MeV}$)

$^{10}\mathrm{Be}(3^-_3)\otimes\Lambda(0s_{1/2})$ $\sqrt{0.737}$
$^{10}\mathrm{Be}(2^+_1)\otimes\Lambda(0p_{3/2})$ $-\sqrt{0.042}$
$^{10}\mathrm{Be}(2^+_1)\otimes\Lambda(0p_{1/2})$ $-\sqrt{0.179}$

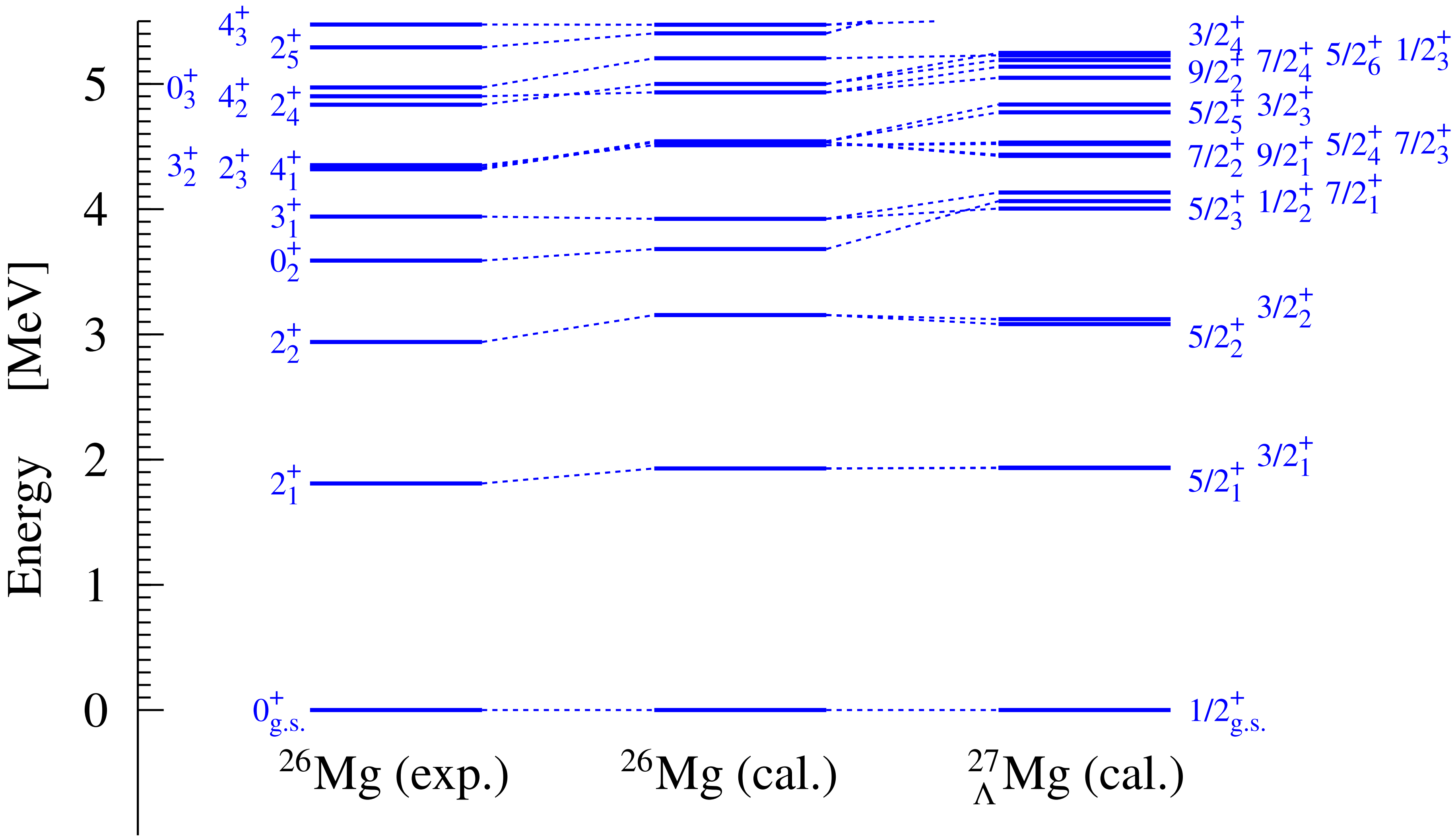
$5/2^-$ ($E_\Lambda = 3.140\,\mathrm{MeV}$)

$^{10}\mathrm{Be}(3^-_3)\otimes\Lambda(0s_{1/2})$ $\sqrt{0.212}$
$^{10}\mathrm{Be}(2^+_1)\otimes\Lambda(0p_{3/2})$ $\sqrt{0.293}$
$^{10}\mathrm{Be}(2^+_1)\otimes\Lambda(0p_{1/2})$ $\sqrt{0.420}$

dominant configurations

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

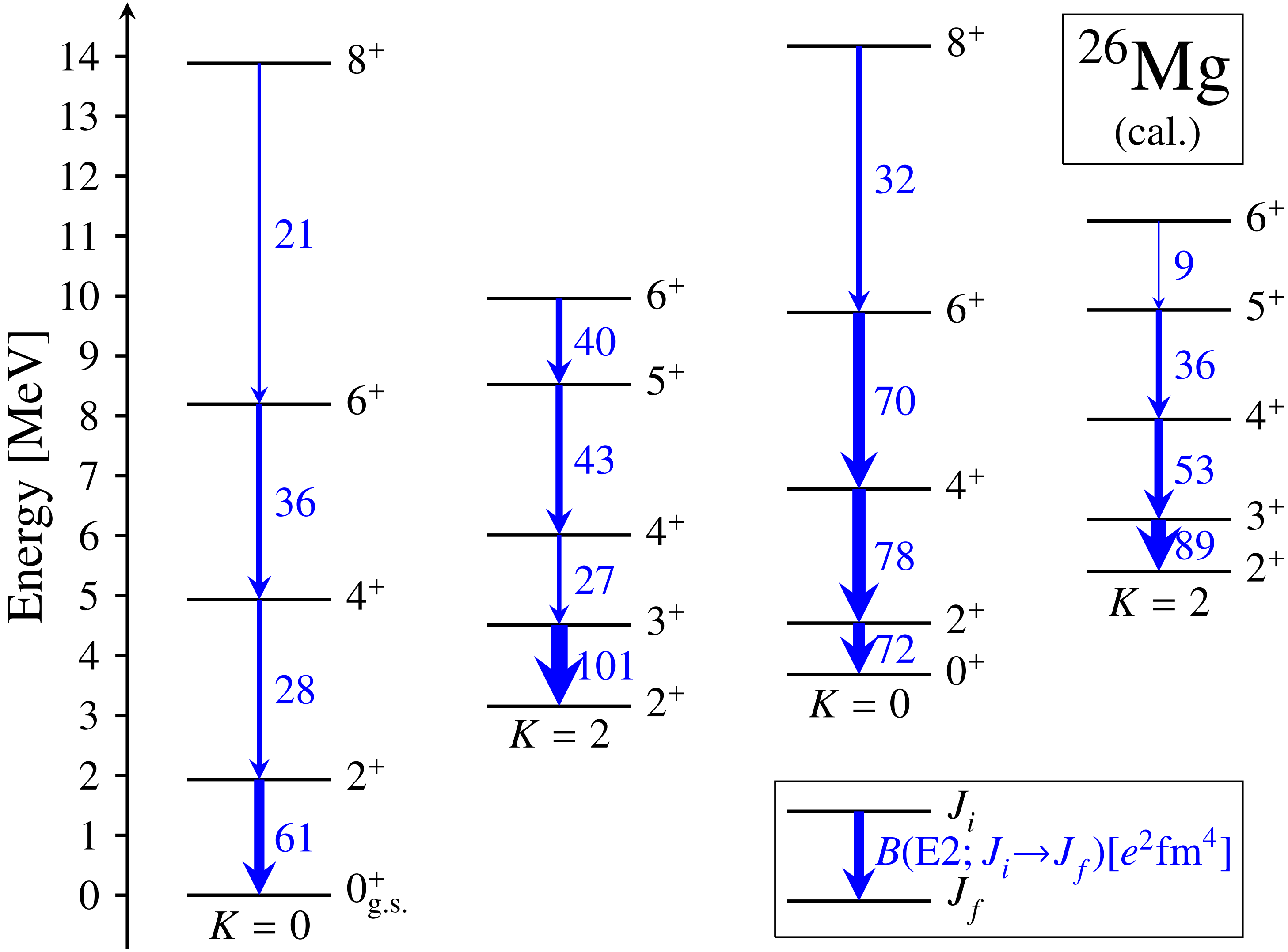
Results : Energy levels of ^{26}Mg and $^{27}_{\Lambda}$Mg



The energy spacings of doublets with the 2_1^+ and 2_2^+ core nuclei are narrow.

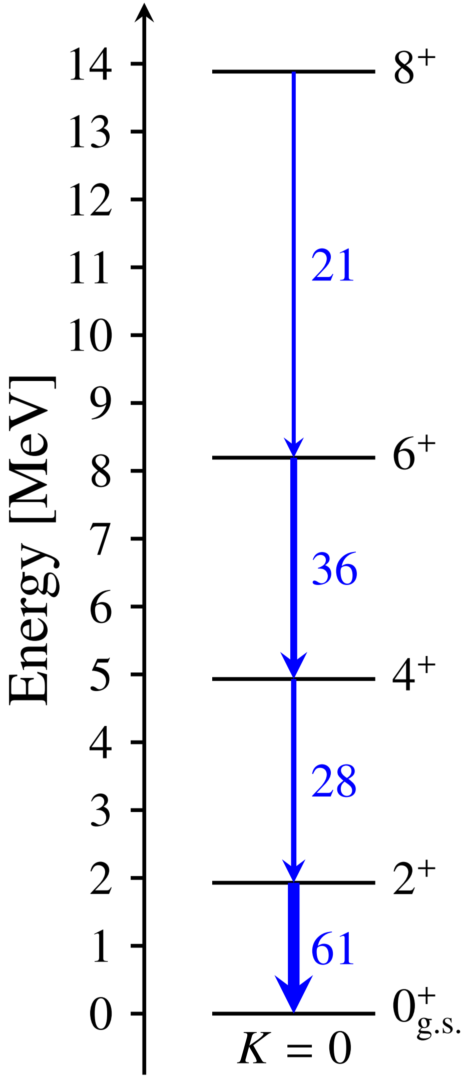
← The 2_1^+ and 2_2^+ core are states with spin $S = 0$ of rotational bands.

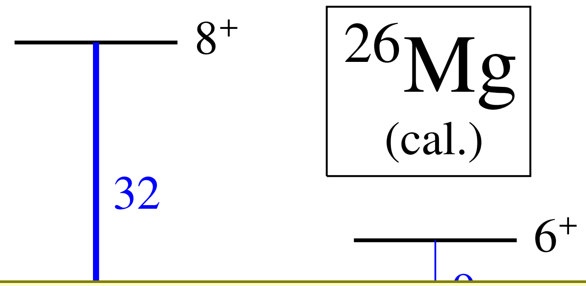
Results : Rotational bands in ^{26}Mg (1)



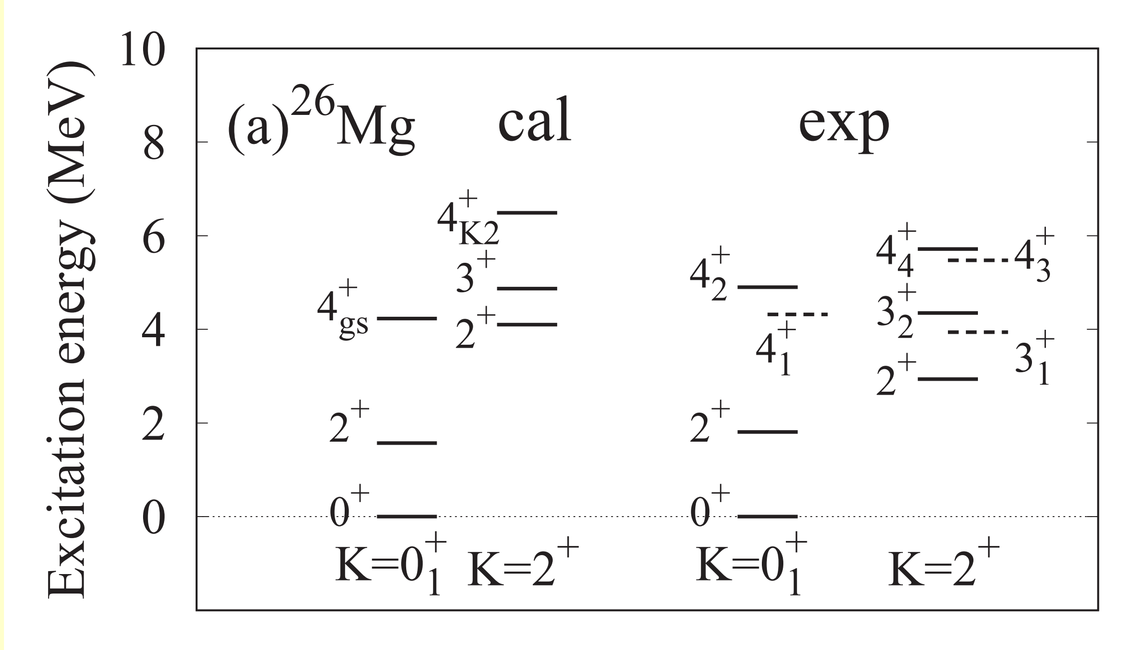
The effective charges are used to reproduce the experimental value $B(E2; 2_1^+ \rightarrow 0_{\rm g.s.^+})_{\rm exp.} = 61.3\, e^2\mathrm{fm}^4$

Results : Rotational bands in ^{26}Mg (2)





The effective charges are used to reproduce



Results in the AMD calculation and the experiment

Y. Kanada-En'yo, Y. Shikata, Y. Chiba, K. Ogata, Phys. Rev. C 102, 014607 (2020)

Λ coupling with rotational bands (1)

In the hypernuclear states consisting of a rotor core with $S = 0$ and a $\Lambda(0s)$ hyperon, a spin-spin ΛN interaction cannot contribute to energy.

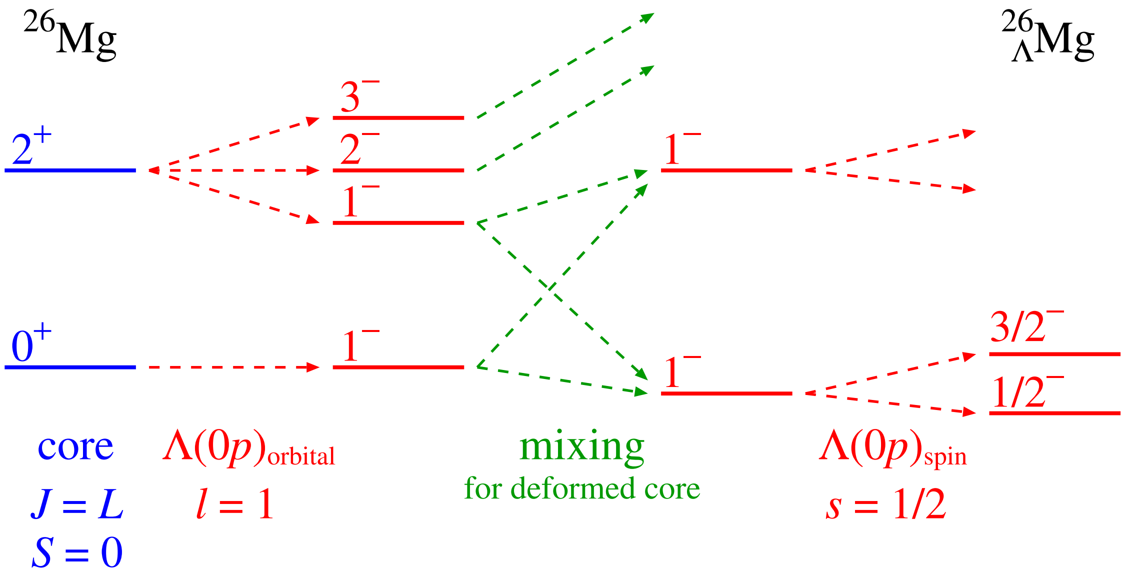
$$\langle\, (LS{=}0)J_{\rm core} \otimes \Lambda(0s)\,|\, V_\sigma(\sigma_N \cdot \sigma_\Lambda)\,|\,(LS{=}0)J_{\rm core} \otimes \Lambda(0s)\,\rangle = 0$$

Thus, the doublet states with the pure rotor core are degenerate.

The low-lying negative-parity states show an admixture of the $\Lambda(0p)$ configurations coupled with nuclear core states having $J_{\rm core}$ and $J_{\rm core} \pm 2$. The mixing amplitude is large for the deformed core.

← It is suggested by the study for ${}^{145\text{–}155}_{\Lambda}$Sm by using a covariant density functional theory.

H. Mei, K. Hagino, J.M. Yao, T. Motoba, Phys. Rev. C 96, 014308 (2017)

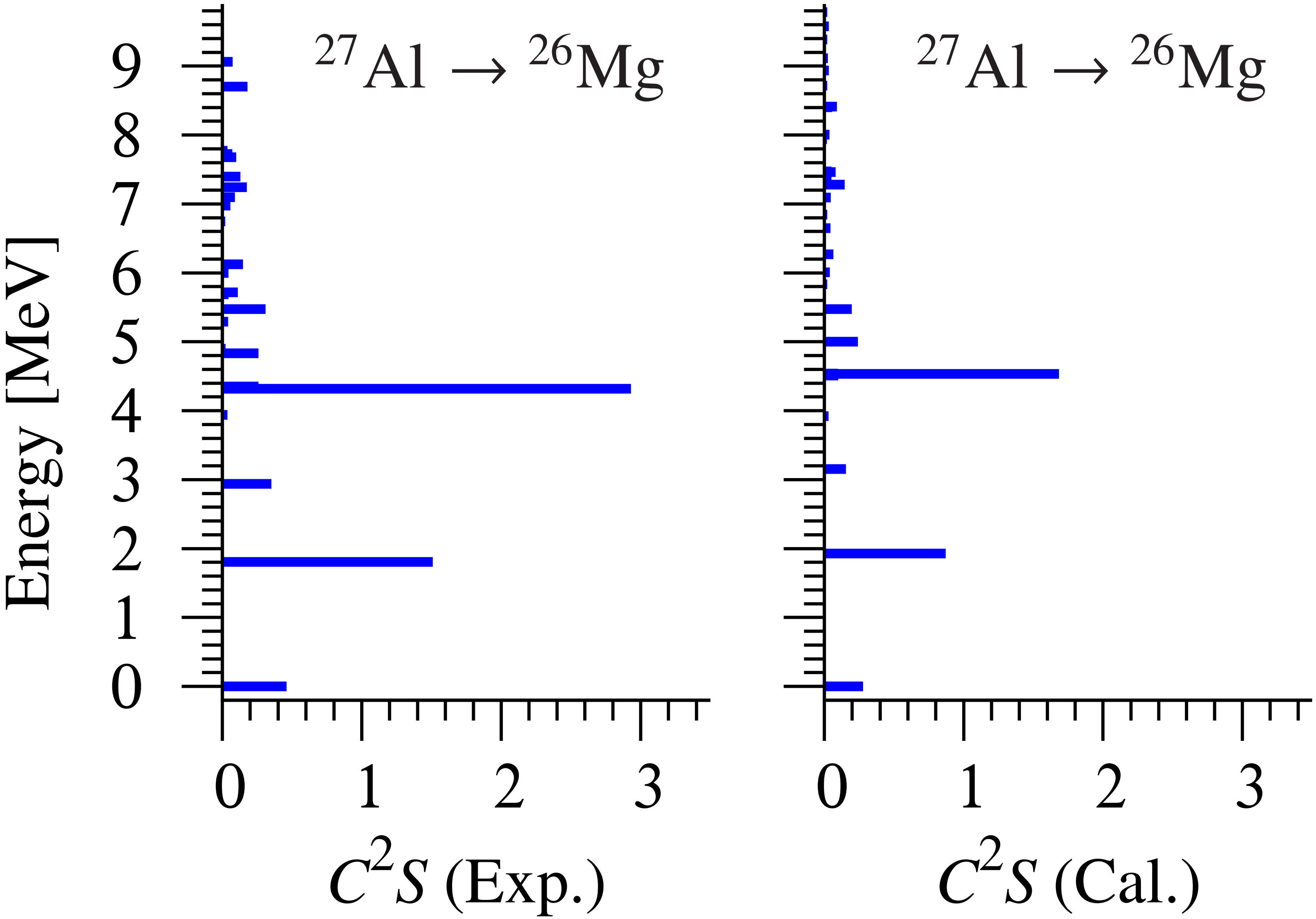


Λ coupling with rotational bands (2)

${}^{27}_{\Lambda}\mathrm{Mg}$

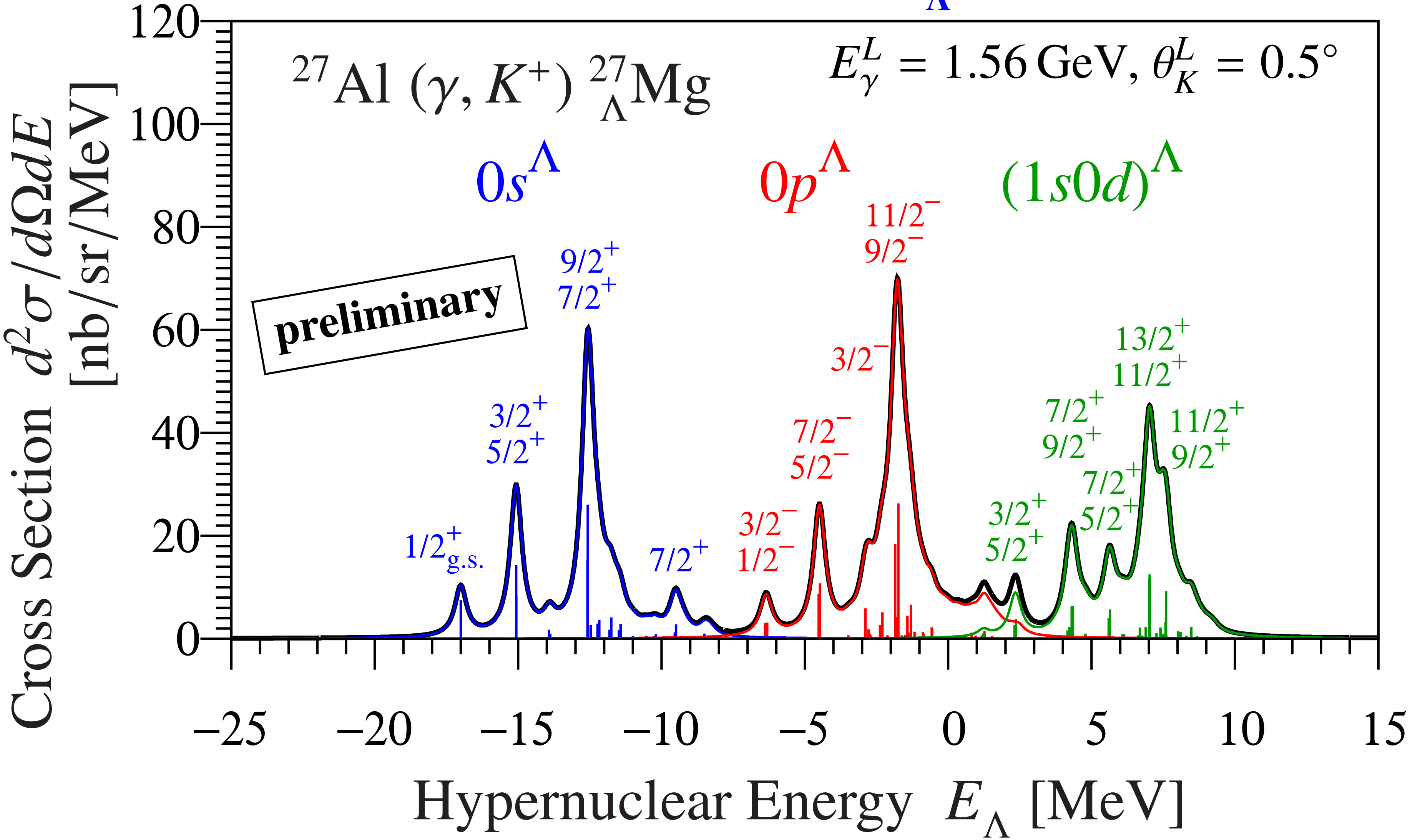
state	E_x [MeV]	configuration ${}^{26}\mathrm{Mg}$	$\otimes$	Λ	percentage [%]
$1/2^+_{\mathrm{g.s.}}$	0.000	$0^+_{\mathrm{g.s.}}$	$\otimes$	$0s^{\Lambda}_{1/2}$	99
$5/2^+_1$	1.932	2^+_1	$\otimes$	$0s^{\Lambda}_{1/2}$	99
$3/2^+_1$	1.935	2^+_1	$\otimes$	$0s^{\Lambda}_{1/2}$	99
$1/2^-$	10.615	$0^+_{\mathrm{g.s.}}$	$\otimes$	$0p^{\Lambda}_{1/2}$	70
		2^+_1	$\otimes$	$0p^{\Lambda}_{3/2}$	28
$3/2^-$	10.685	$0^+_{\mathrm{g.s.}}$	$\otimes$	$0p^{\Lambda}_{3/2}$	68
		2^+_1	$\otimes$	$0p^{\Lambda}_{3/2}$	15
		2^+_1	$\otimes$	$0p^{\Lambda}_{1/2}$	15

Results : Spectroscopic factors of proton pickup reaction from ^{27}Al



(Exp.) J. Vernotte et al., Phys. Rev. C 48, 205 (1993)

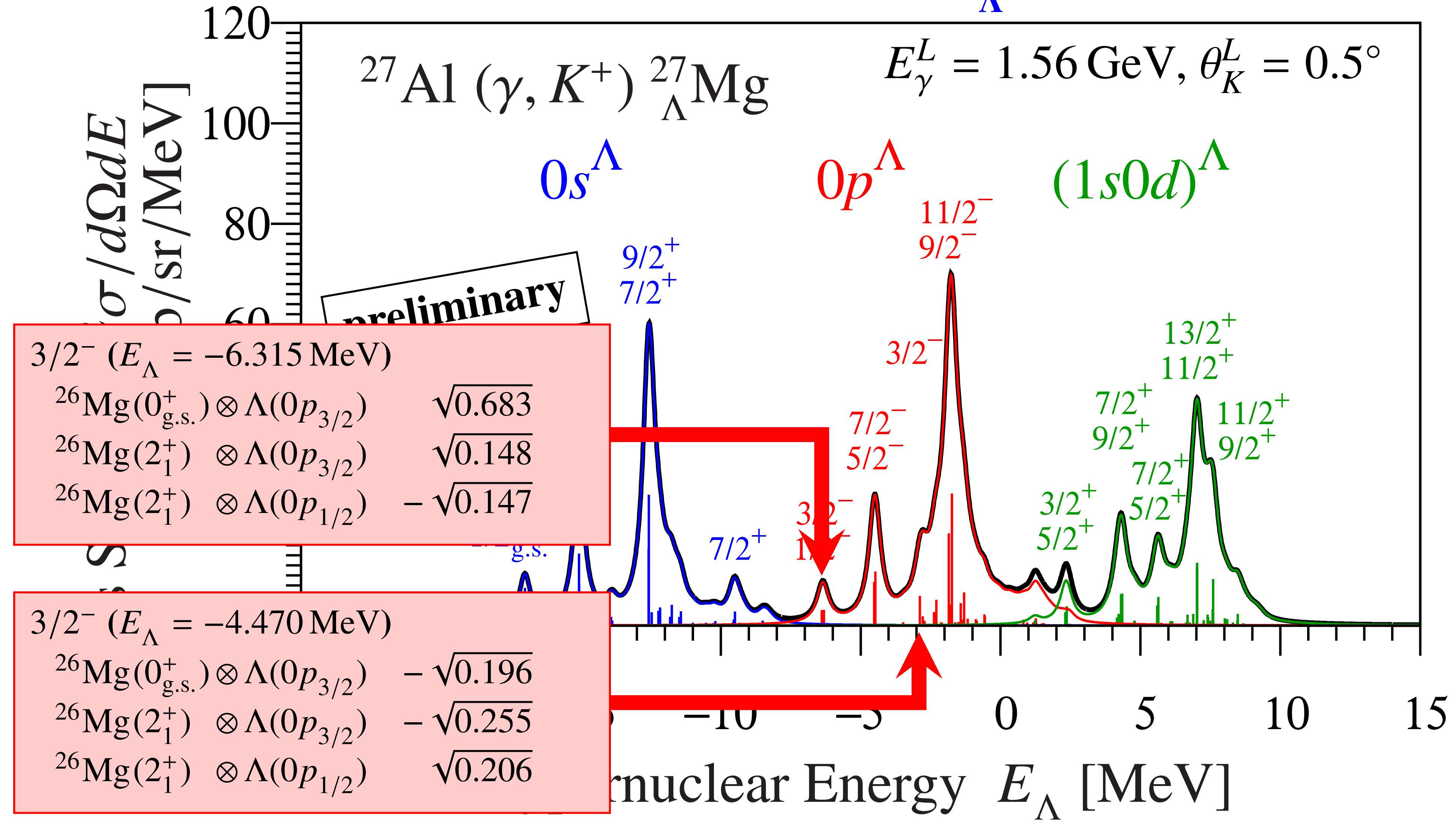
Results : Cross sections of the $^{27}\mathrm{Al}\,(\gamma, K^{+})\,^{27}_{\Lambda}\mathrm{Mg}$ reaction (1)



FWHM = 0.50 MeV

blue $J^{+};\ J^{+}_{\mathrm{core}} \otimes 0s^{\Lambda}$ **red** $J^{-};\ J^{+}_{\mathrm{core}} \otimes 0p^{\Lambda}$ **green** $J^{+};\ J^{+}_{\mathrm{core}} \otimes (1s0d)^{\Lambda}$

Results : Cross sections of the $^{27}\mathrm{Al}\,(\gamma, K^+)\,^{27}_{\Lambda}\mathrm{Mg}$ reaction (2)



$3/2^-$ ($E_\Lambda = -6.315$ MeV)

$^{26}\mathrm{Mg}(0^+_{\mathrm{g.s.}}) \otimes \Lambda(0p_{3/2})$	$\sqrt{0.683}$
$^{26}\mathrm{Mg}(2^+_1) \otimes \Lambda(0p_{3/2})$	$\sqrt{0.148}$
$^{26}\mathrm{Mg}(2^+_1) \otimes \Lambda(0p_{1/2})$	$-\sqrt{0.147}$

$3/2^-$ ($E_\Lambda = -4.470$ MeV)

$^{26}\mathrm{Mg}(0^+_{\mathrm{g.s.}}) \otimes \Lambda(0p_{3/2})$	$-\sqrt{0.196}$
$^{26}\mathrm{Mg}(2^+_1) \otimes \Lambda(0p_{3/2})$	$-\sqrt{0.255}$
$^{26}\mathrm{Mg}(2^+_1) \otimes \Lambda(0p_{1/2})$	$\sqrt{0.206}$

FWHM = 0.50 MeV

blue $J^+;\ J^+_{\mathrm{core}} \otimes 0s^\Lambda$ **red** $J^-;\ J^+_{\mathrm{core}} \otimes 0p^\Lambda$ **green** $J^+;\ J^+_{\mathrm{core}} \otimes (1s0d)^\Lambda$

Summary

We have calculated the energy levels and the production cross sections for the $^{11}_{\Lambda}\mathrm{Be}$ and $^{27}_{\Lambda}\mathrm{Mg}$ hypernuclei by using the shell-model wave functions.

- **In the energy levels of $^{11}_{\Lambda}\mathrm{Be}$ and $^{27}_{\Lambda}\mathrm{Mg}$, the energy spacings of doublets with the 2^+_1 and 2^+ core nuclei are narrow because these core are states with spin $S = 0$ of rotational bands.**
- **In $^{11}_{\Lambda}\mathrm{Be}$ and $^{27}_{\Lambda}\mathrm{Mg}$, the low-lying negative-parity states show an admixture of the $\Lambda(0p)$ configurations coupled with nuclear core states having 0^+ and 2^+, which are deformed.**
- **For the $^{11}\mathrm{B}\ (\gamma, K^+)$ reaction, the DWIA calculation shows the large cross sections of unnatural-parity states with intershell mixing of the nuclear core-excited states having different parities.**