27th International Nuclear Physics Conference
(INPC2019)

Jul. 29 – Aug. 2, 2019

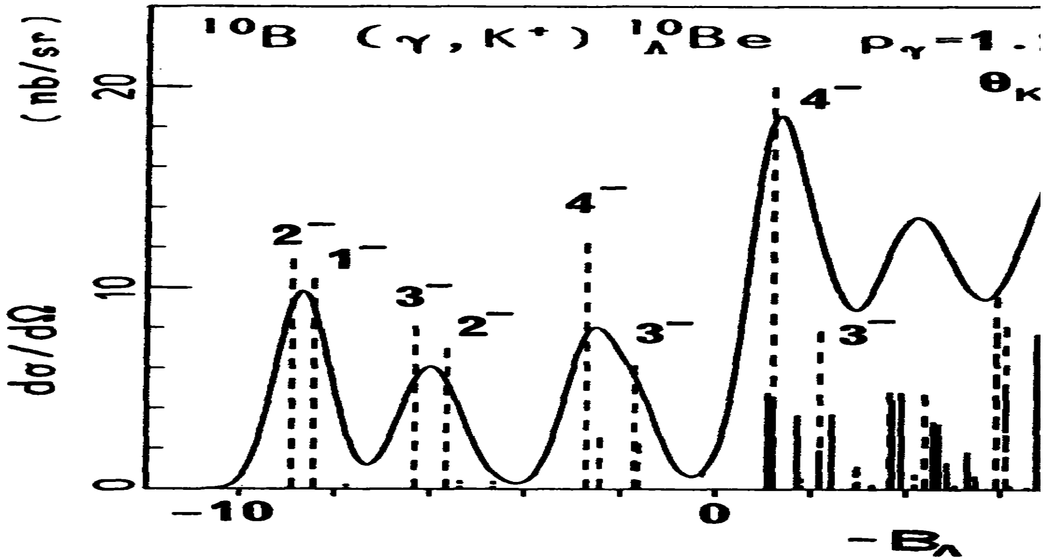
Structures and production cross sections of p-shell Lambda-hypernuclei calculated with multi-configuration shell model

Atsushi UMEYA (Nippon Inst. of Tech.)

Toshio MOTOBA (Osaka E-C Univ., YITP)

Kazunori ITONAGA (Gifu Univ.)

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



Shell-model prediction

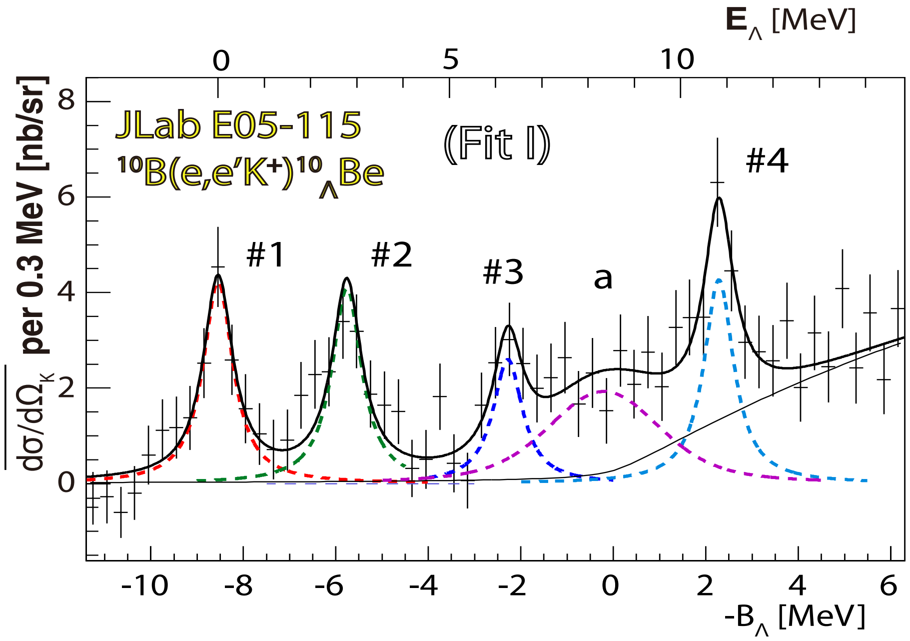
T. Motoba *et al.*,
PTPS117, 123 (1994)

Core nucleus calculated with standard *p*-shell model

Λ in *s*-orbit

Recent experimental result

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

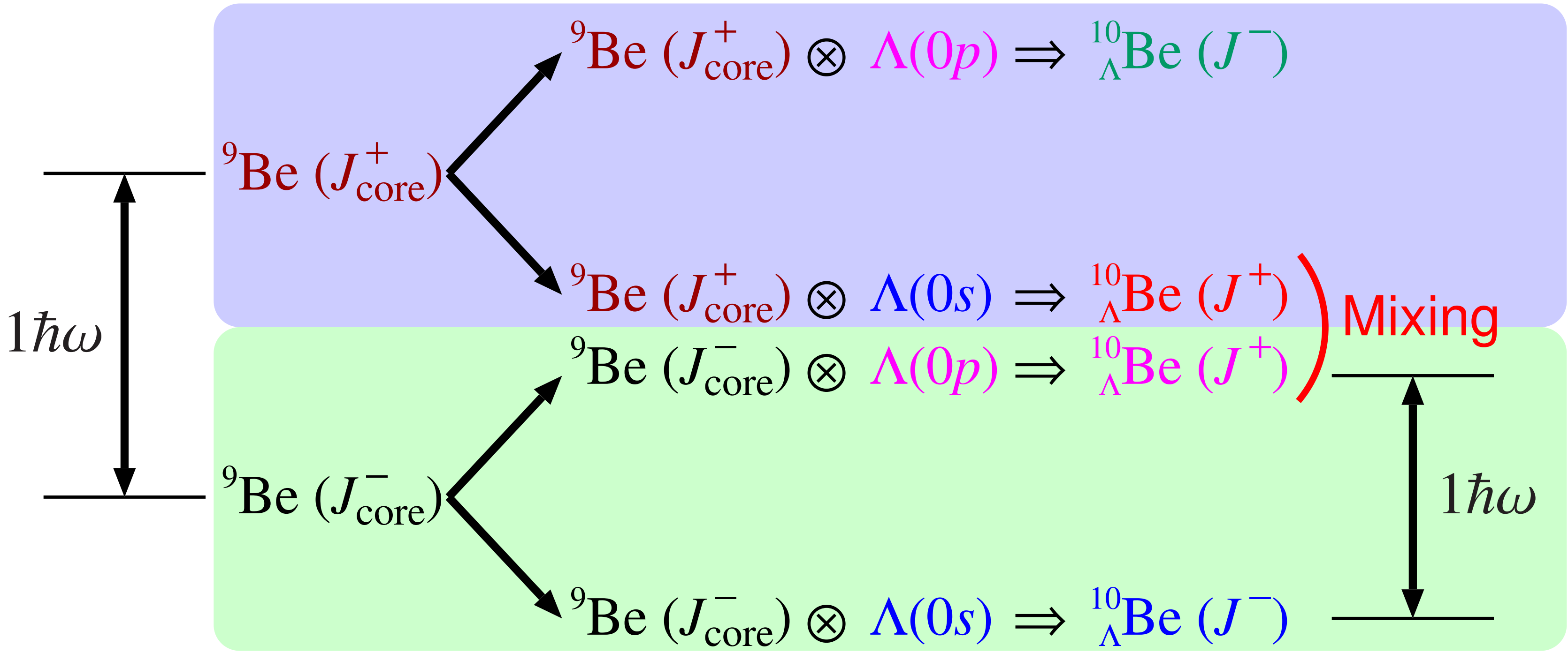


This experiment has confirmed the major peaks (#1, #2, #3, #4) predicted in DWIA by emplying the Λ particle in *s*-orbit coupled with the nuclear core states confined within the *p*-shell configuration. However, it is interesting to observe extra strengths at $E_\Lambda = 0$ MeV excitation (a).

⇓

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

Configration mixing in ${}^{10}_{\Lambda}\mathrm{Be}$ unnatural parity states



$^{9}\mathrm{Be}\ (J^{+}_{\mathrm{core}}) \otimes \Lambda(0p) \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}\ (J^{-})$

$^{9}\mathrm{Be}\ (J^{+}_{\mathrm{core}})$

$^{9}\mathrm{Be}\ (J^{+}_{\mathrm{core}}) \otimes \Lambda(0s) \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}\ (J^{+})$

$1\hbar\omega$

Mixing

$^{9}\mathrm{Be}\ (J^{-}_{\mathrm{core}}) \otimes \Lambda(0p) \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}\ (J^{+})$

$^{9}\mathrm{Be}\ (J^{-}_{\mathrm{core}})$

$1\hbar\omega$

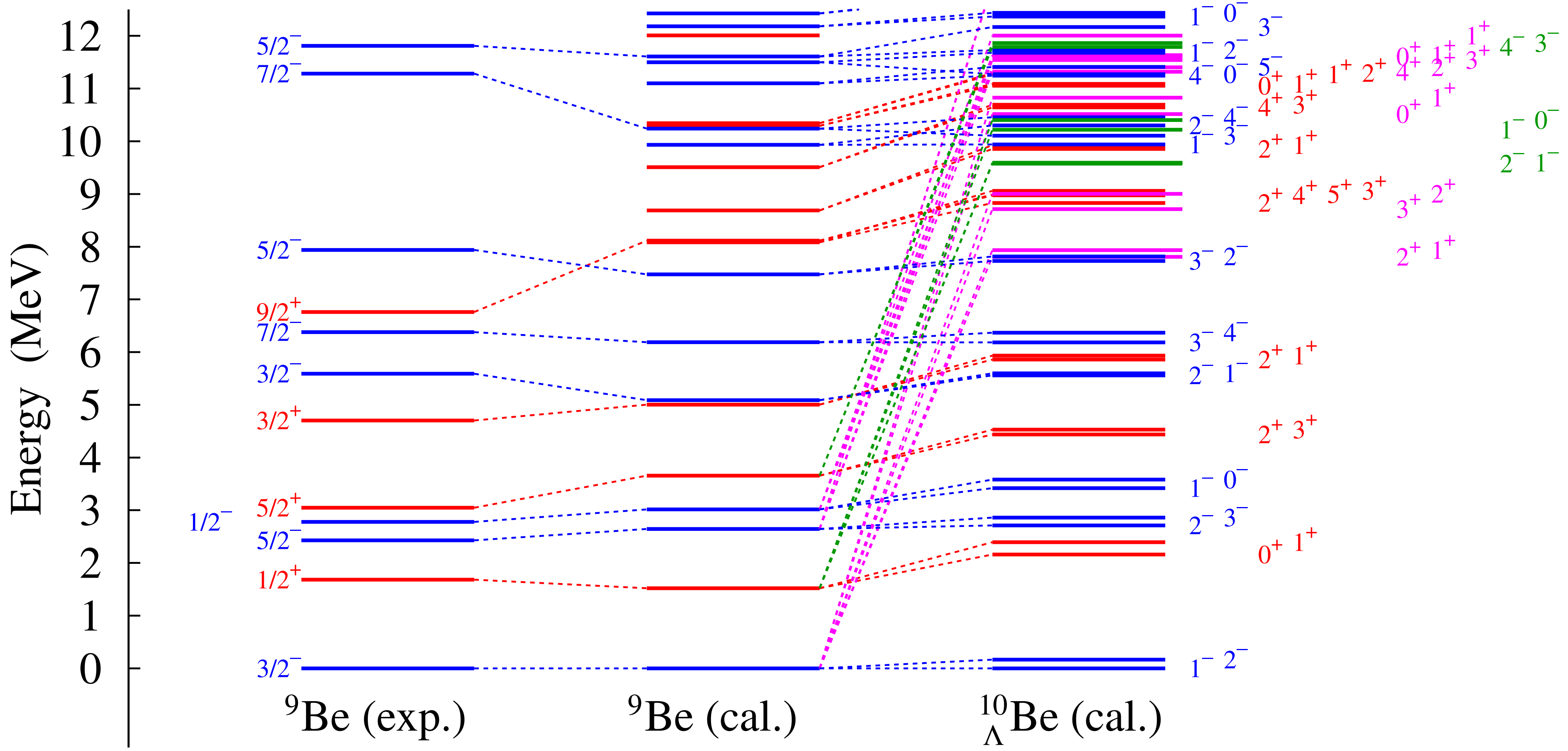
$^{9}\mathrm{Be}\ (J^{-}_{\mathrm{core}}) \otimes \Lambda(0s) \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}\ (J^{-})$

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

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

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

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



dominant configurations

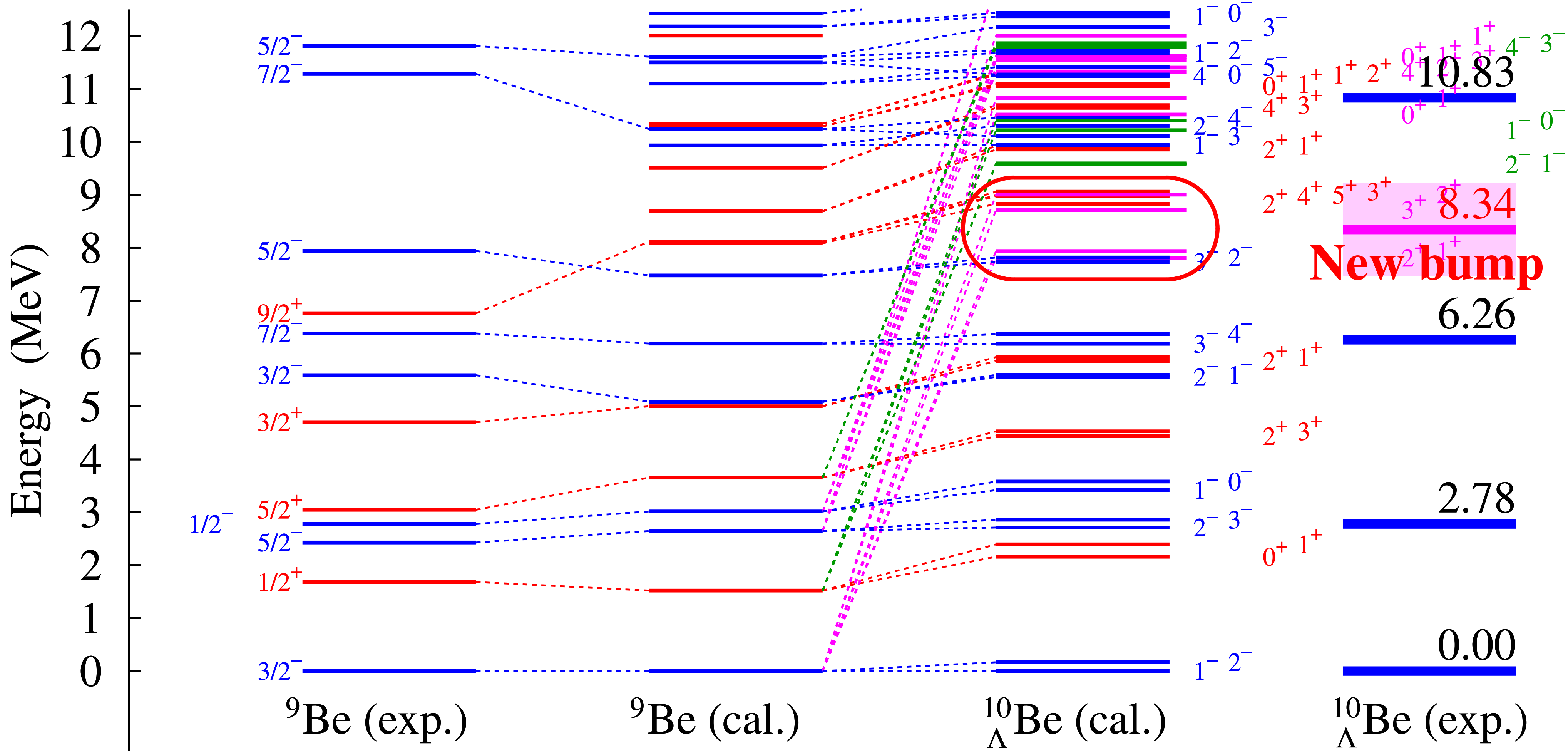
blue $J^-;\ {}^{9}\mathrm{Be}(J^-_{\mathrm{core}}) \otimes \Lambda(0s)$

green $J^+;\ {}^{9}\mathrm{Be}(J^+_{\mathrm{core}}) \otimes \Lambda(0p)$

magenta $J^+;\ {}^{9}\mathrm{Be}(J^-_{\mathrm{core}}) \otimes \Lambda(0p)$

red $J^+;\ {}^{9}\mathrm{Be}(J^+_{\mathrm{core}}) \otimes \Lambda(0s)$

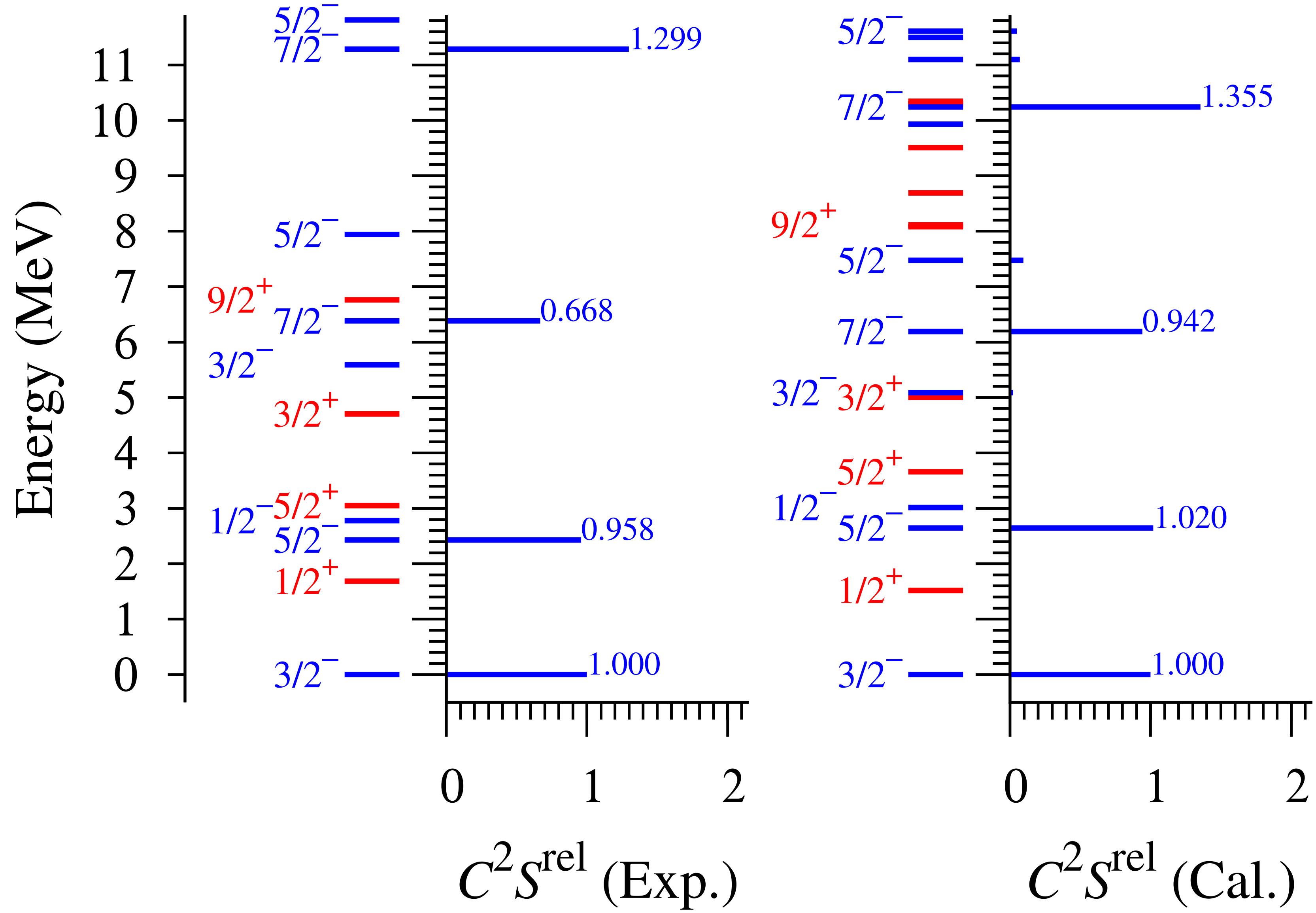
Results : Energy levels of $^{10}_{\Lambda}$Be (comparison with JLab experiments)



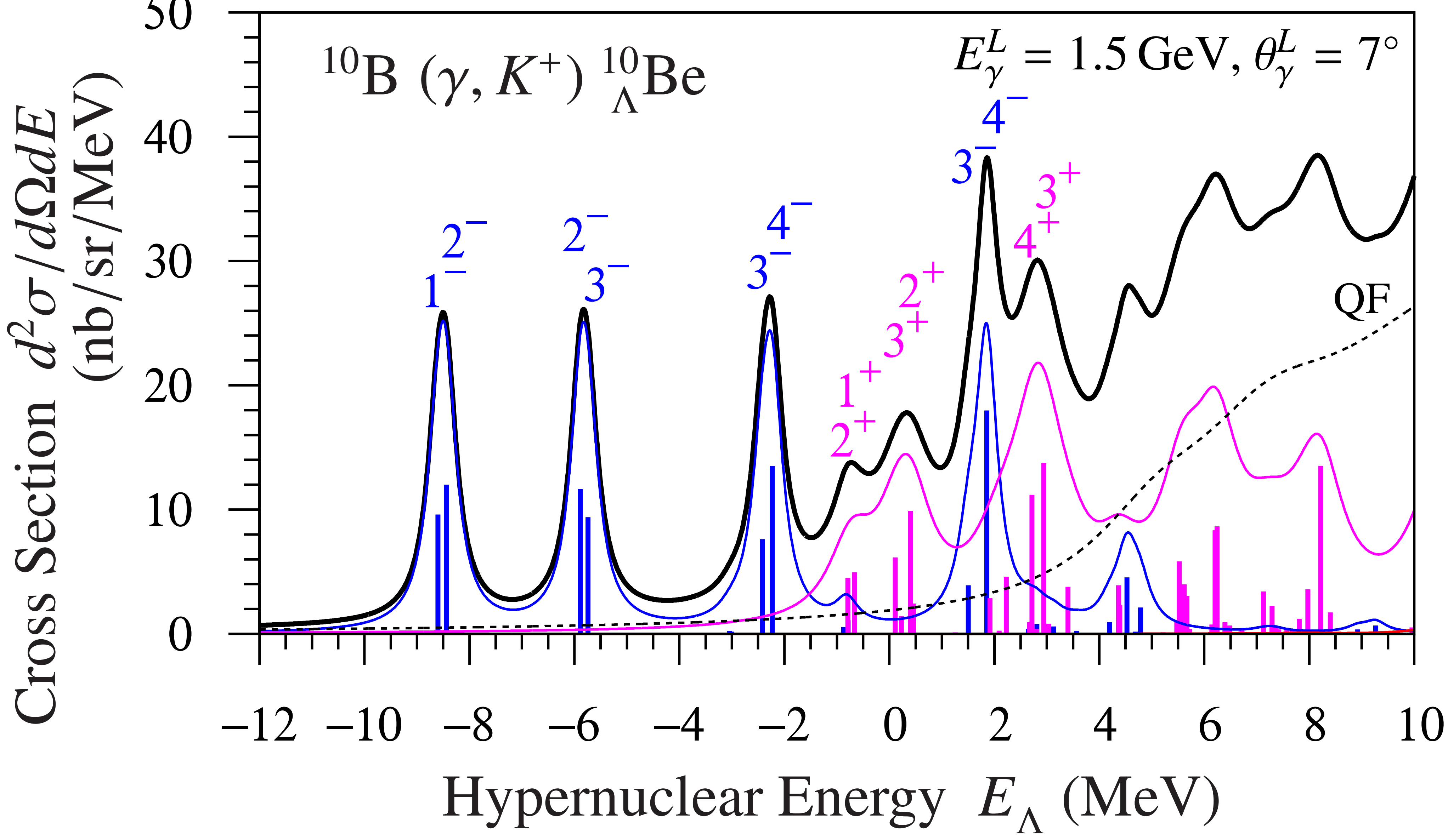
⇑

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

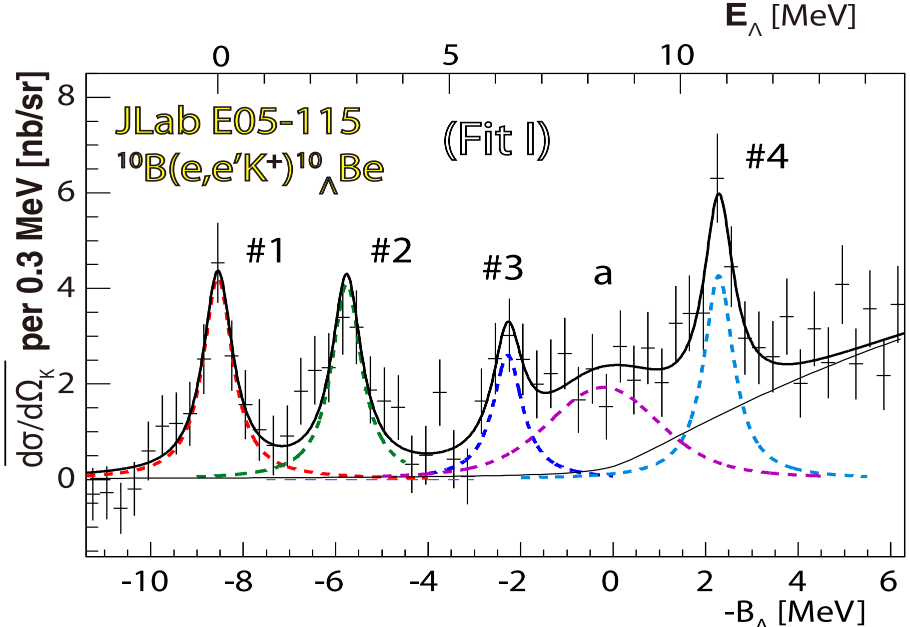
Results : Spectroscopic factors of the pickup reaction, $^{10}\mathrm{B} \rightarrow {}^{9}\mathrm{Be}$



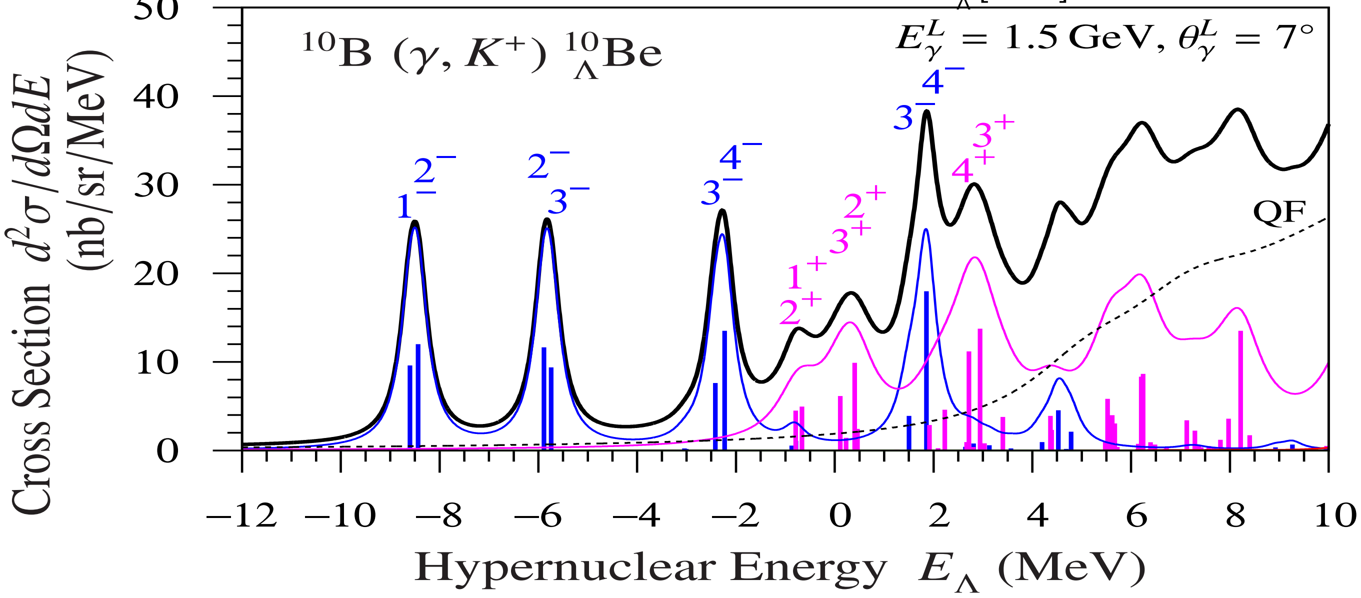
Results : Cross sections of the ^{10}B (γ, K^+) $^{10}_{\Lambda}$Be reaction (1)



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



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



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 (3)

E_γ = 1.5 GeV
θ = 7 deg

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

^{9}Be (J_i)

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

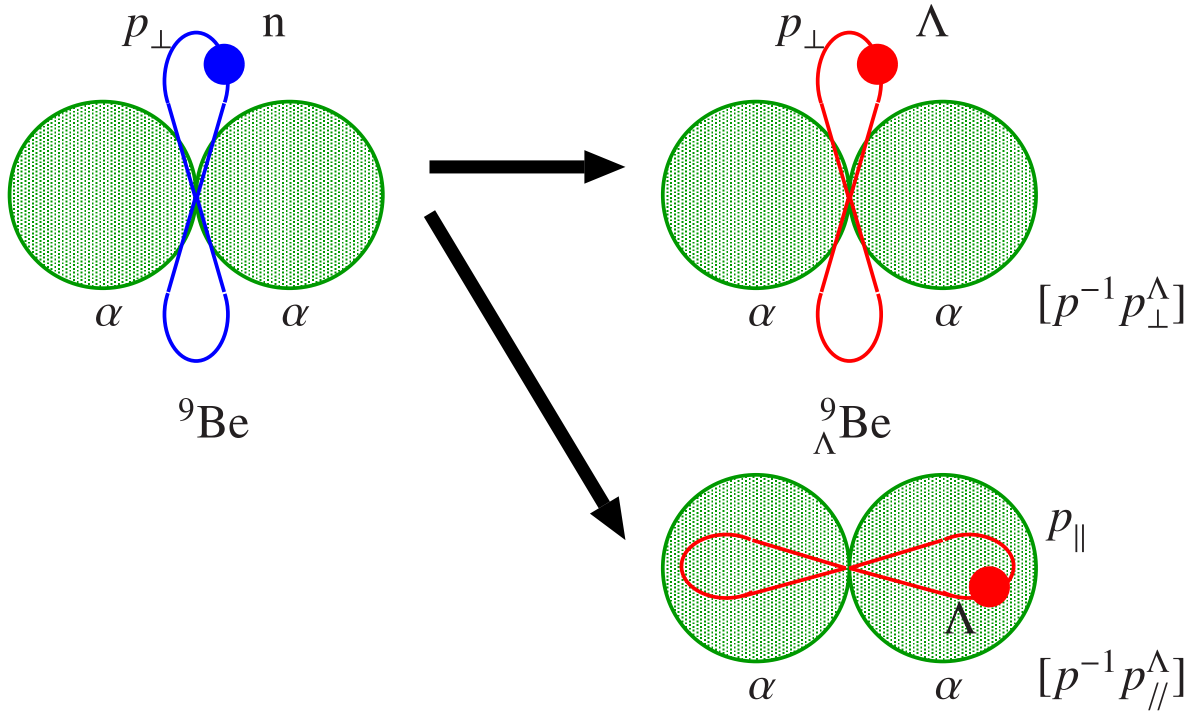
EXP **Fit I**

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%

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



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.

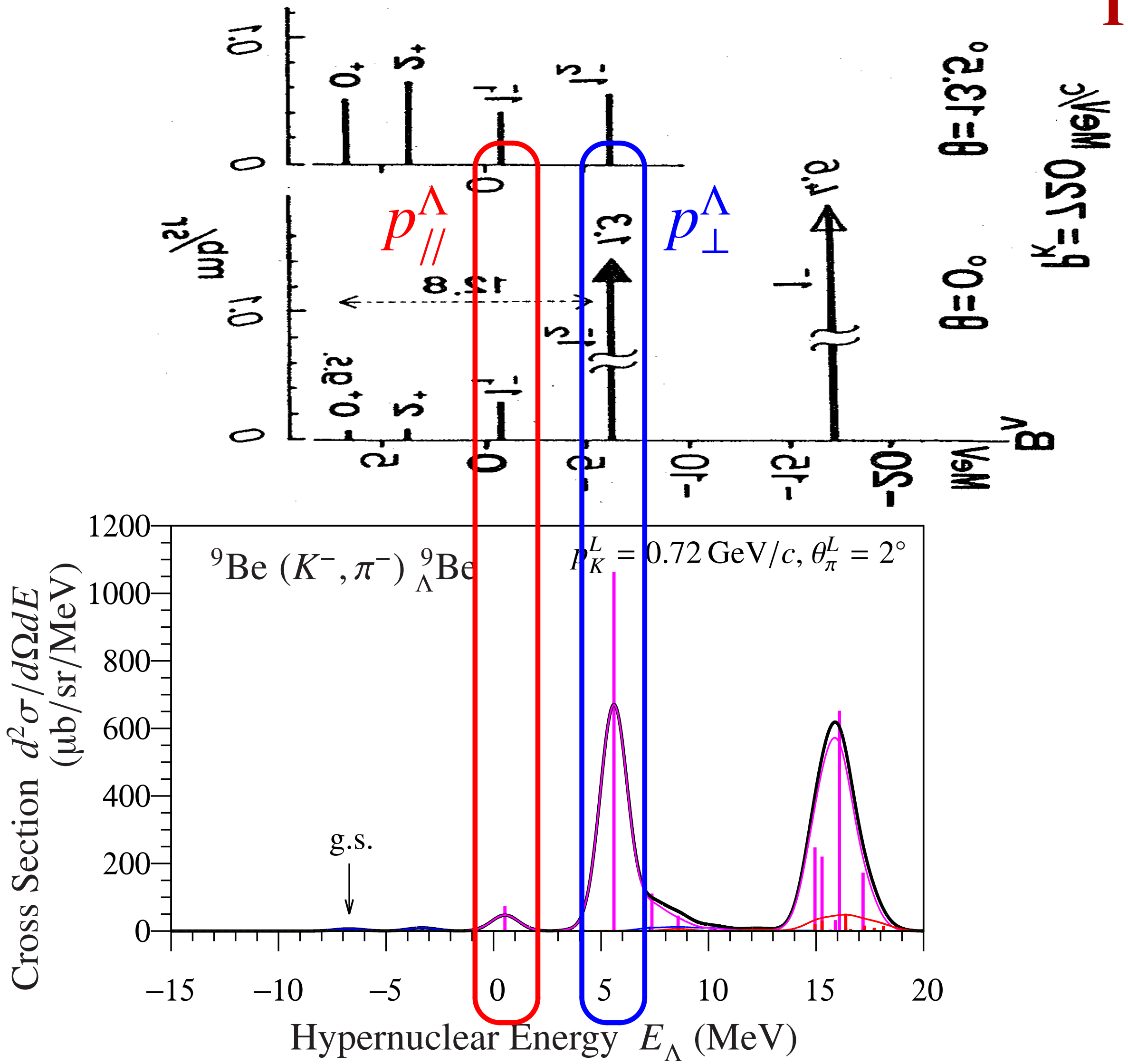
T. Motoba *et al.*, PTPS81, 42 (1985)

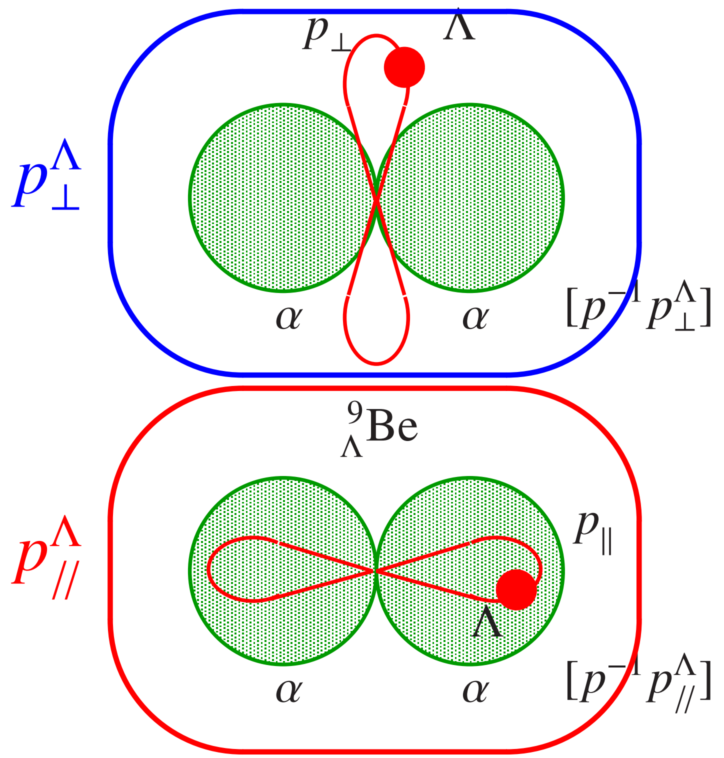
The $p_{//}$ state tends to the configuration with an SU(3) classification $[f](\lambda\mu) = [54](50)$ called supersymmetric.

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

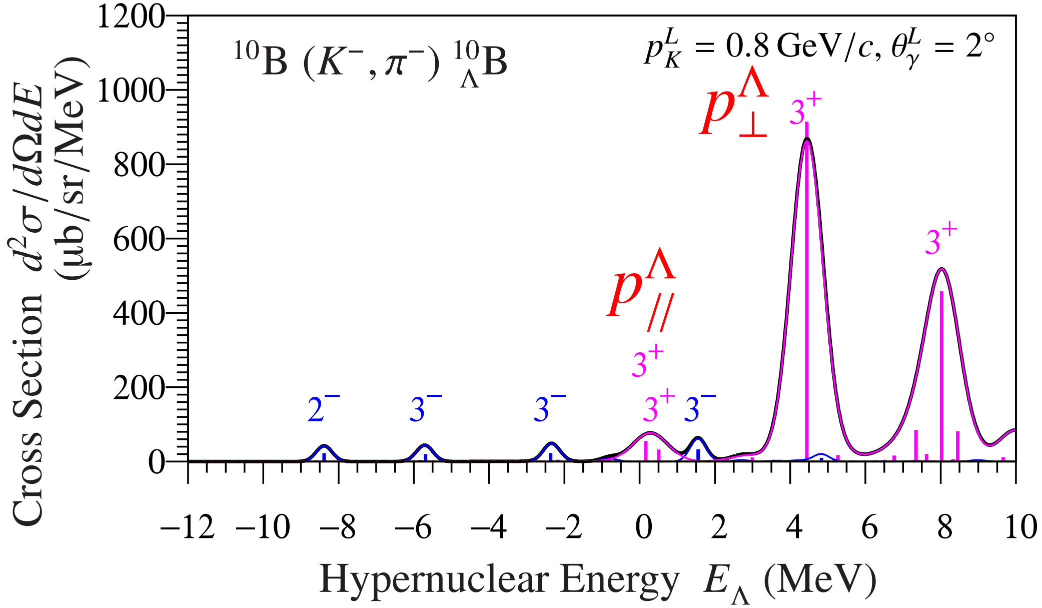
[$p^{-1}p^{\Lambda}_{\perp}$] and [$p^{-1}p^{\Lambda}_{//}$] states of $^{9}_{\Lambda}\mathrm{Be}$ (2)

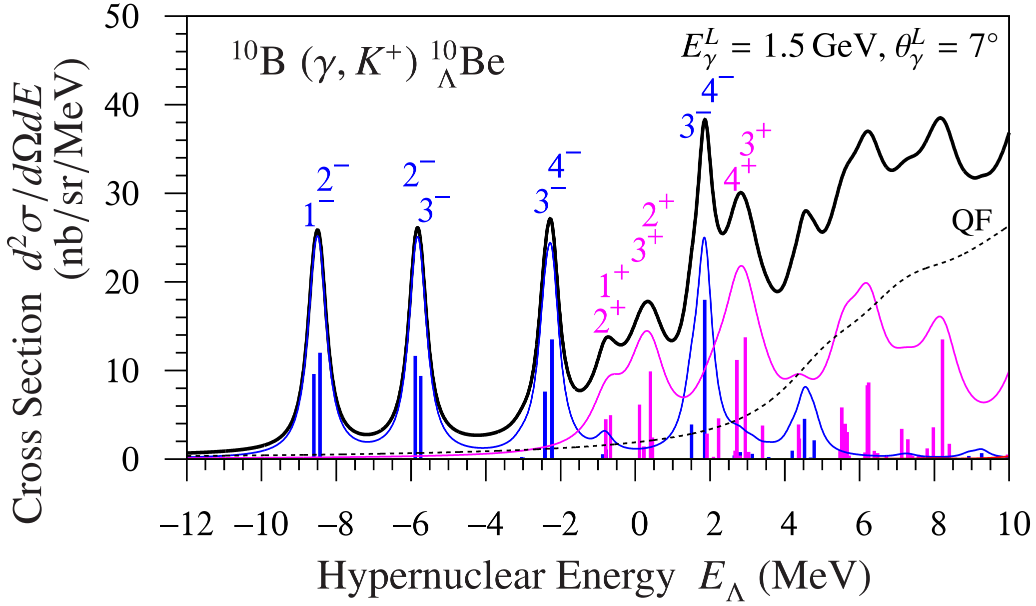
T. Motoba *et al.*, PTPS81, 42 (1985)





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





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

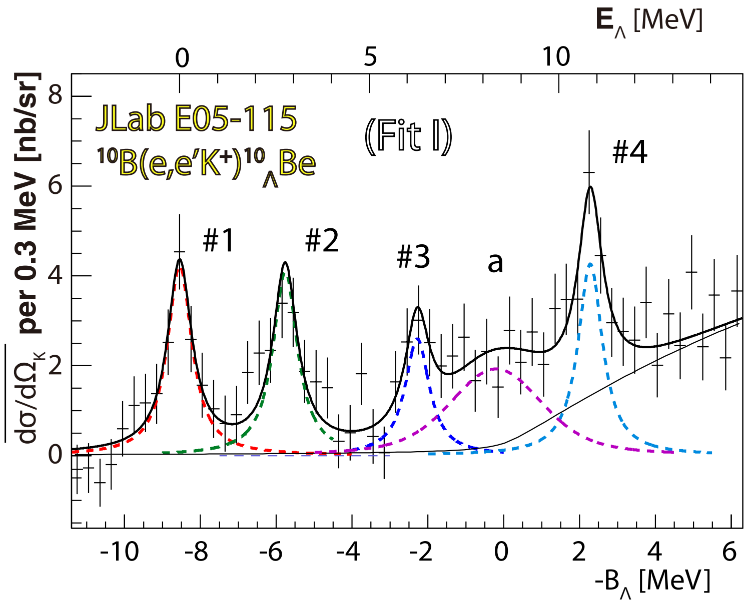
The small peak at $E_\Lambda = 0\ \mathrm{MeV}$ corresponds to the new bump and is explained as a mixture of s^Λ and p^Λ states.

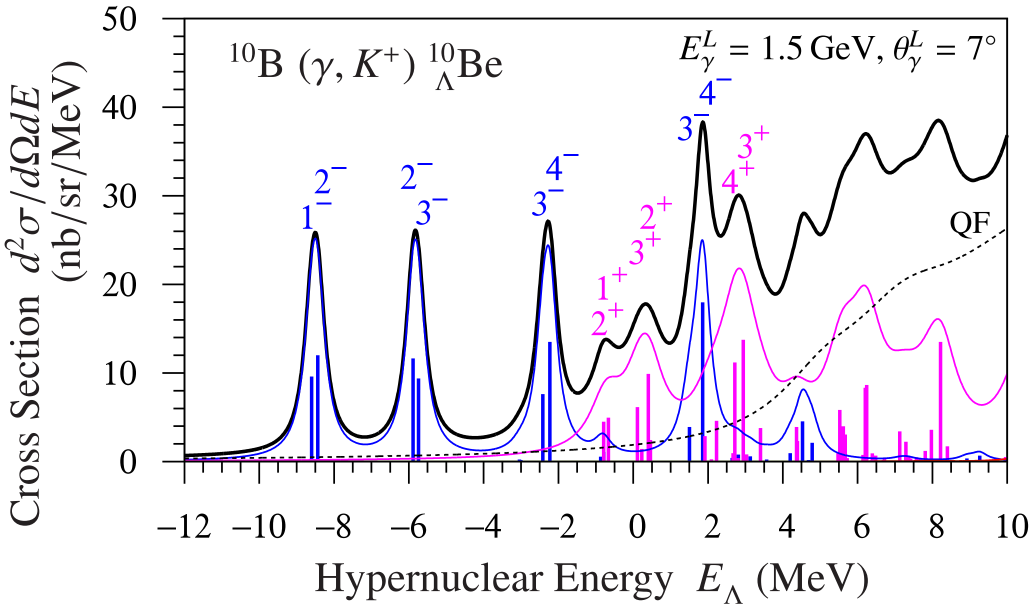
The large peak at $E_\Lambda = 4.4\ \mathrm{MeV}$ in $^{10}_{\Lambda}\mathrm{Be}$ corresponds to the $[p^{-1}p^\Lambda_\perp]$ state in $^{9}_{\Lambda}\mathrm{Be}$ ($^9\mathrm{Be}$ analog state).

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

Summary

We have calculated the cross sections in $^{10}_{\Lambda}\mathrm{Be}$ productions by using the extended shell model to describe the unnatural-parity nuclear core.





- **Our new calculation explains the new bump in the JLab experimental results as a sum of cross sections of some J^+ states.**
- **These states have a large mixture of unnatural- and natural-parity nuclear-core states by strong ΛN interaction.**
- **The new bump in $^{10}_{\Lambda}\mathrm{Be}$ corresponds to the $[p^{-1}p^{\Lambda}_{//}]$ state in $^{9}_{\Lambda}\mathrm{Be}$.**