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Hypernuclear photoproduction spectra calculated with multi-configuration wave functions

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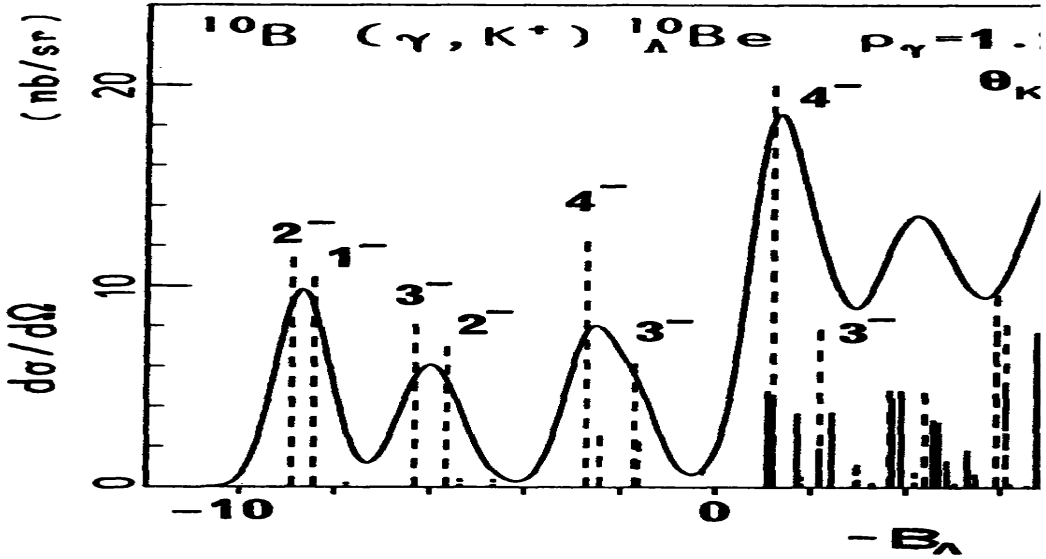
Recent $(e,e'K^+)$ reaction experiments done at the Jefferson Lab



Shell-model prediction

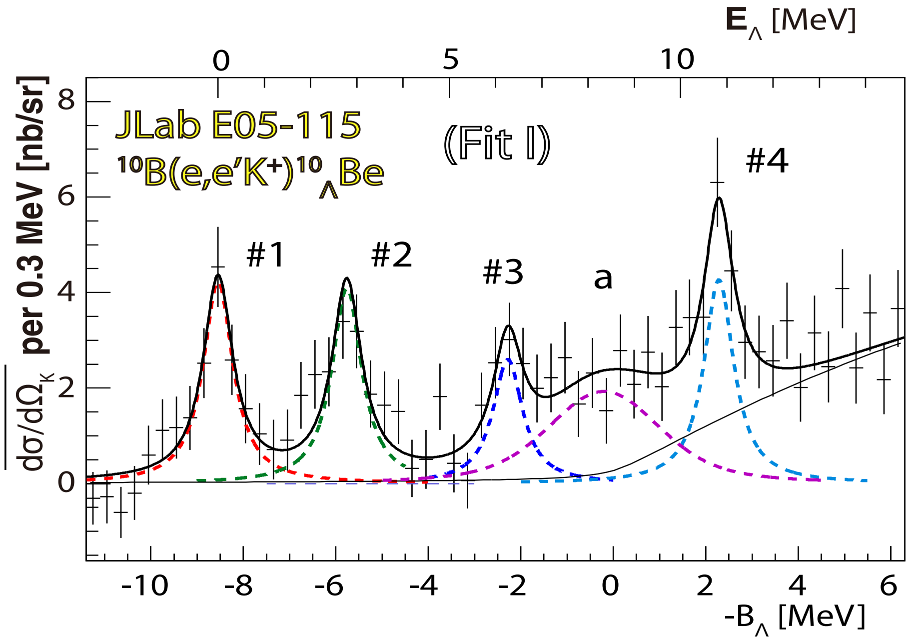
T. Motoba *et al.*,
PTPS117, 123 (1994)

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).

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

Extension of the model space in the shell model ($^{10}_{\Lambda}$Be case)

Model space for ^{9}Be core

(A) standard model space $J^{-}_{\rm core}$ $\boxed{(0s)^4\,(0p)^5}$ $(0p\text{-}0h)$

(B) extended model space $J^{+}_{\rm core}$ $\boxed{(0s)^3\,(0p)^6} \oplus \boxed{(0s)^4\,(0p)^4\,(sd)^1}$ $(1p\text{-}1h)$

Standard model space for $^{10}_{\Lambda}$Be

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

Extension (1) 1*p*-1*h* (1ℏω) core excitation is taken into account

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

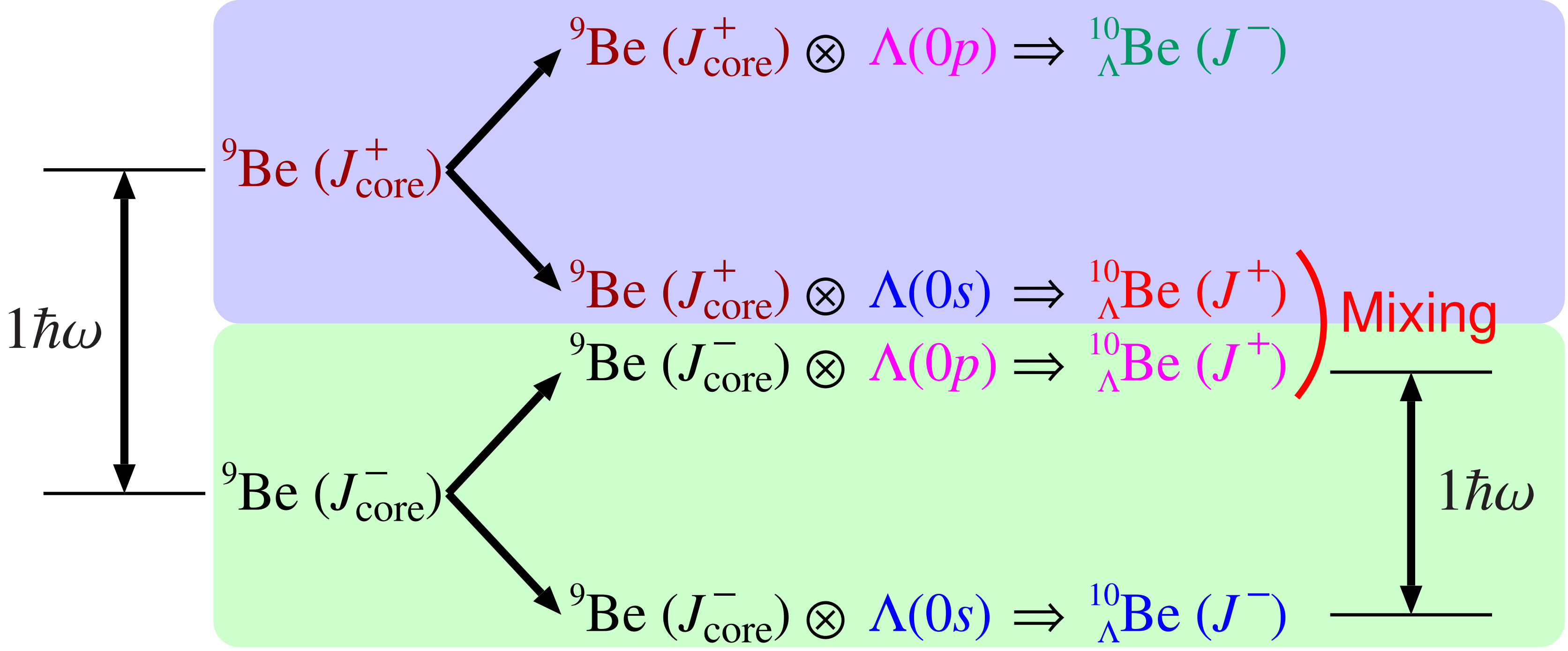
(c) $\boxed{J^{+}_{\rm core} \otimes 0s^{\Lambda}} \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}(J^{+})$ **(d)** $\boxed{J^{+}_{\rm core} \otimes 0p^{\Lambda}} \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}(J^{-})$

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

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

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

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



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

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

$1\hbar\omega$

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

Mixing

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

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

$1\hbar\omega$

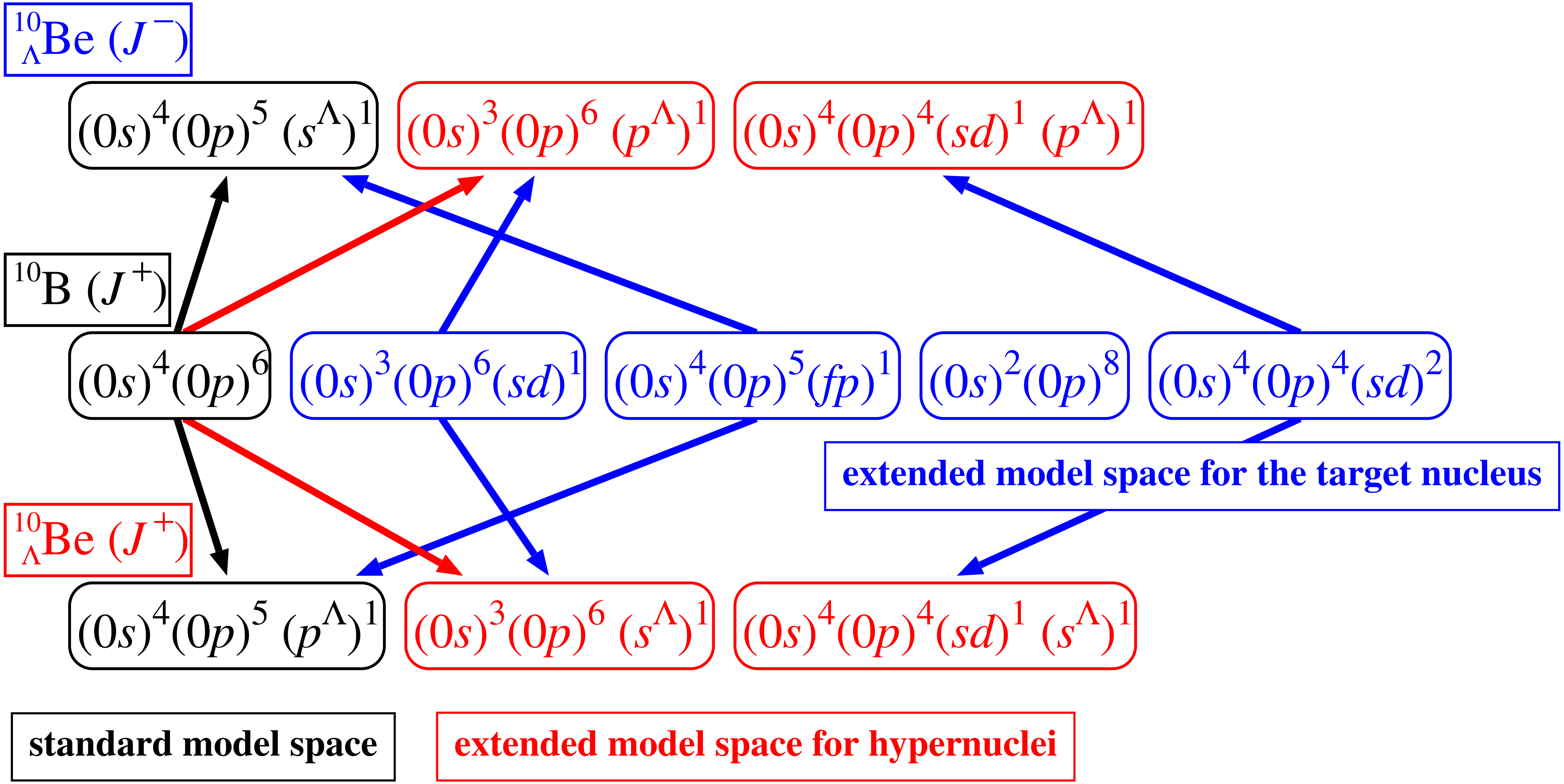
$^{9}\mathrm{Be}\ (J^{-}_{\mathrm{core}}) \otimes \Lambda(0s) \Rightarrow {}^{10}_{\Lambda}\mathrm{Be}\ (J^{-})$

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.

Extended model space for target nucleus $^{10}\mathrm{B}$



${}^{10}_{\Lambda}\mathrm{Be}\ (J^{-})$

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

$(0s)^3(0p)^6\ (p^{\Lambda})^1$

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

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

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

$(0s)^3(0p)^6(sd)^1$

$(0s)^4(0p)^5(fp)^1$

$(0s)^2(0p)^8$

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

extended model space for the target nucleus

${}^{10}_{\Lambda}\mathrm{Be}\ (J^{+})$

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

$(0s)^3(0p)^6\ (s^{\Lambda})^1$

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

standard model space

extended model space for hypernuclei

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

ΛN interaction and Λ single-particle energy

$\langle N\Lambda|V|N\Lambda\rangle$ **Nijmegen NSC97e**

Th. A. Rijken, V. G. J. Stoks, Y. Yamamoto, PRC59, 21 (1999)

ε_s^Λ and ε_p^Λ are determined to reproduce the #1 (2^-) and #6 (3^+) peaks in ${}^{12}_{\Lambda}$B production cross-section.

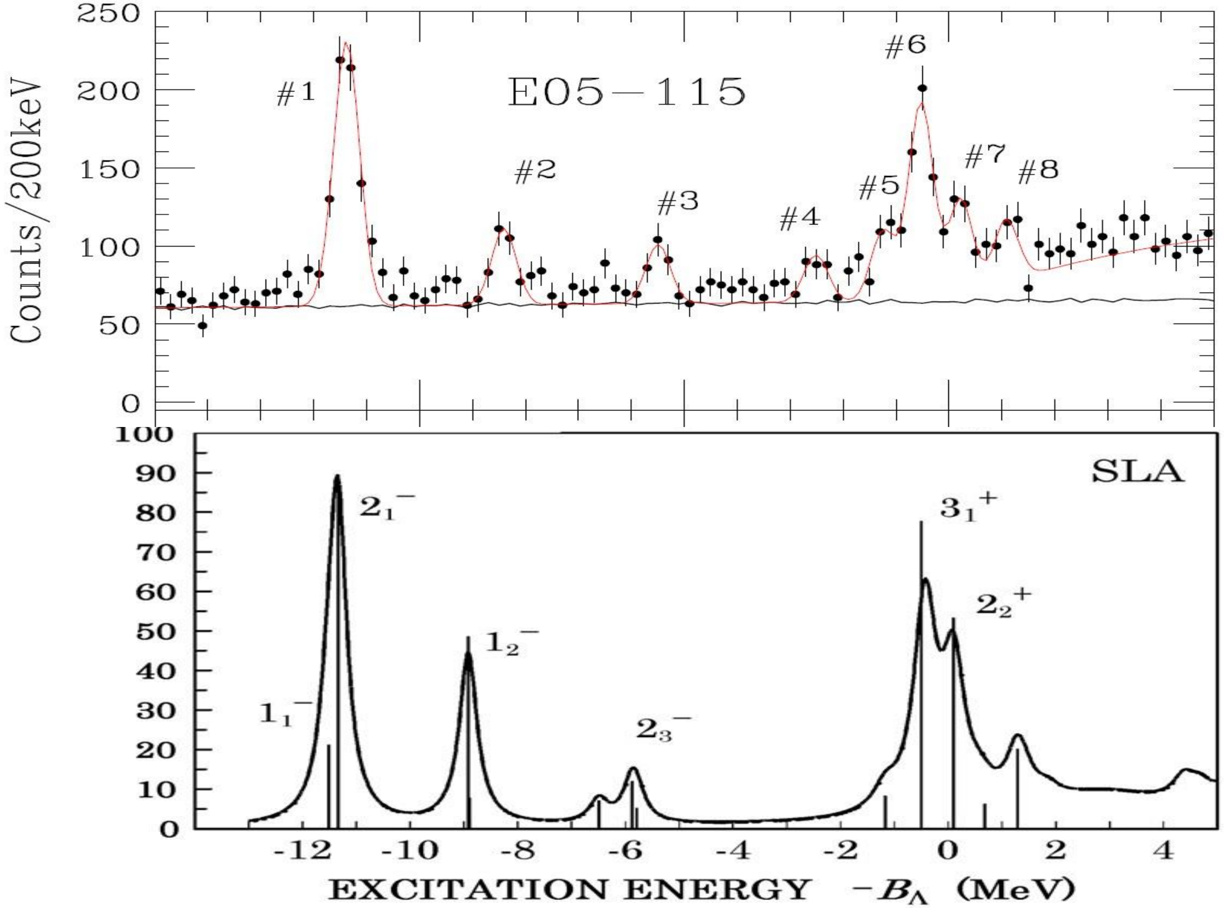
ε_s^Λ and ε_p^Λ are applied to ${}^{10}_{\Lambda}$Be.

JLab Hall C, E05-115

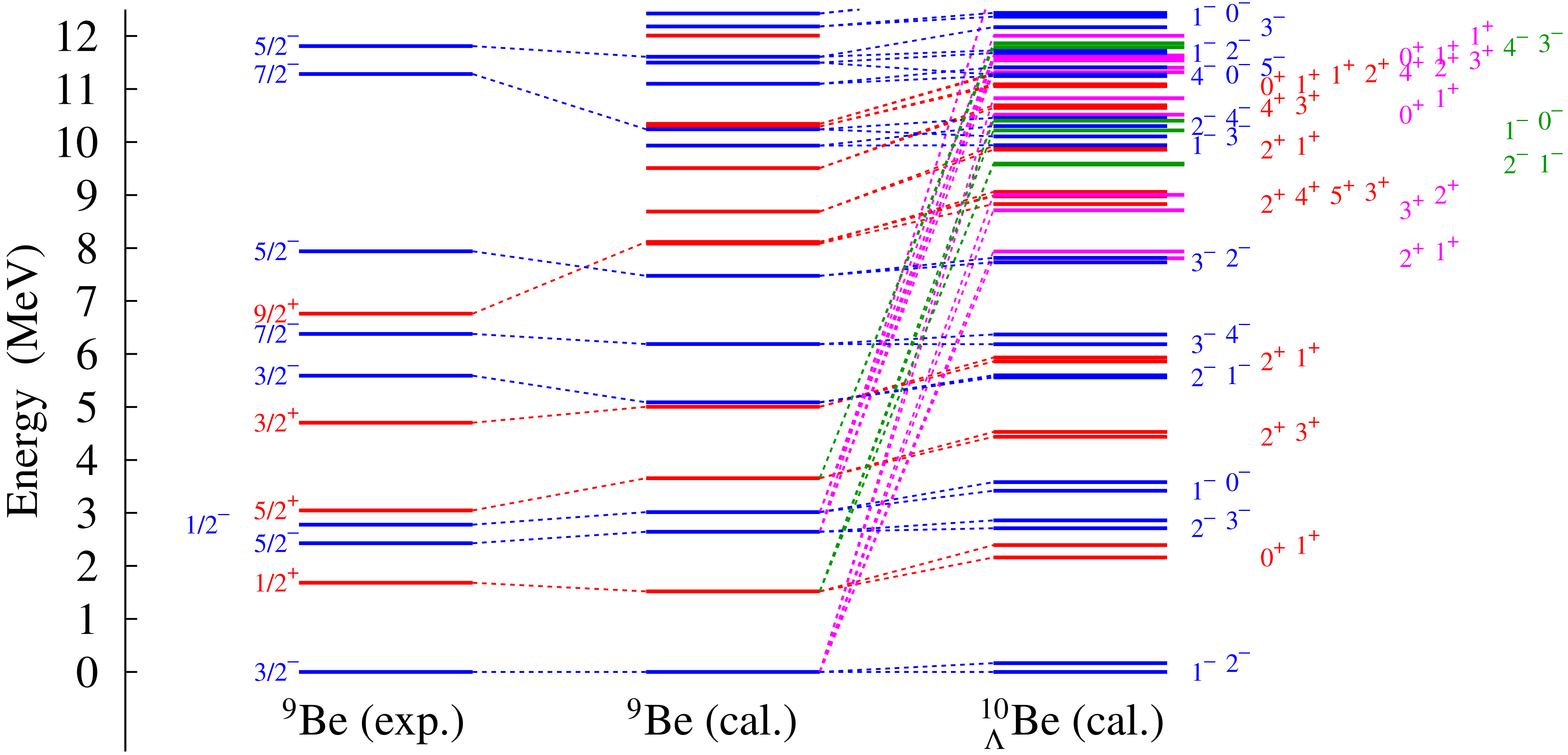
L. Tang *et al.*,
PRC90, 034320 (2014)

Theoretical calculation

T. Motoba *et al.*,
PTPS185, 224 (2010)



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



dominant configurations

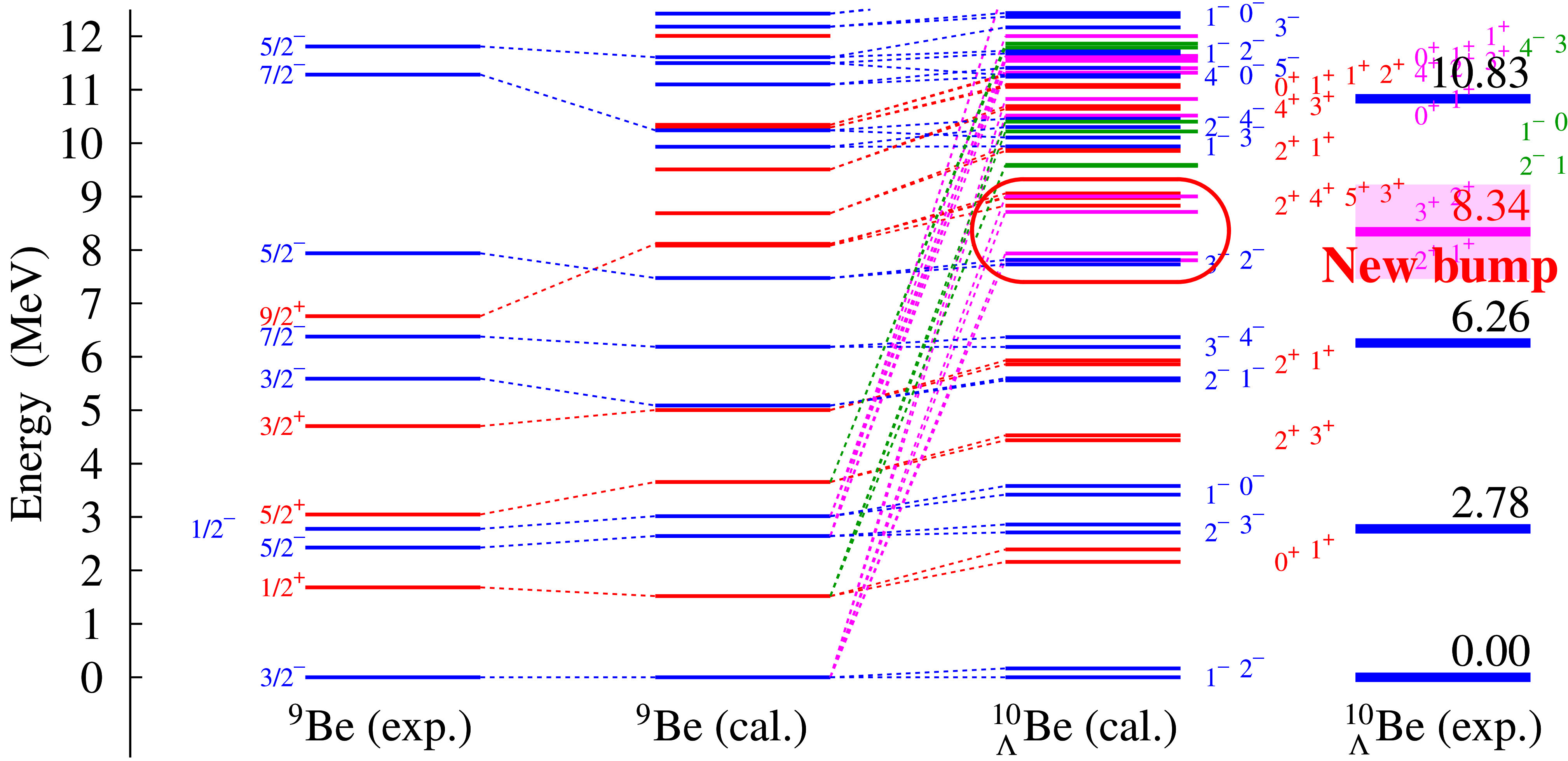
blue $J^-;\ ^{9}\mathrm{Be}(J^-_{\mathrm{core}}) \otimes \Lambda(0s)$

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)



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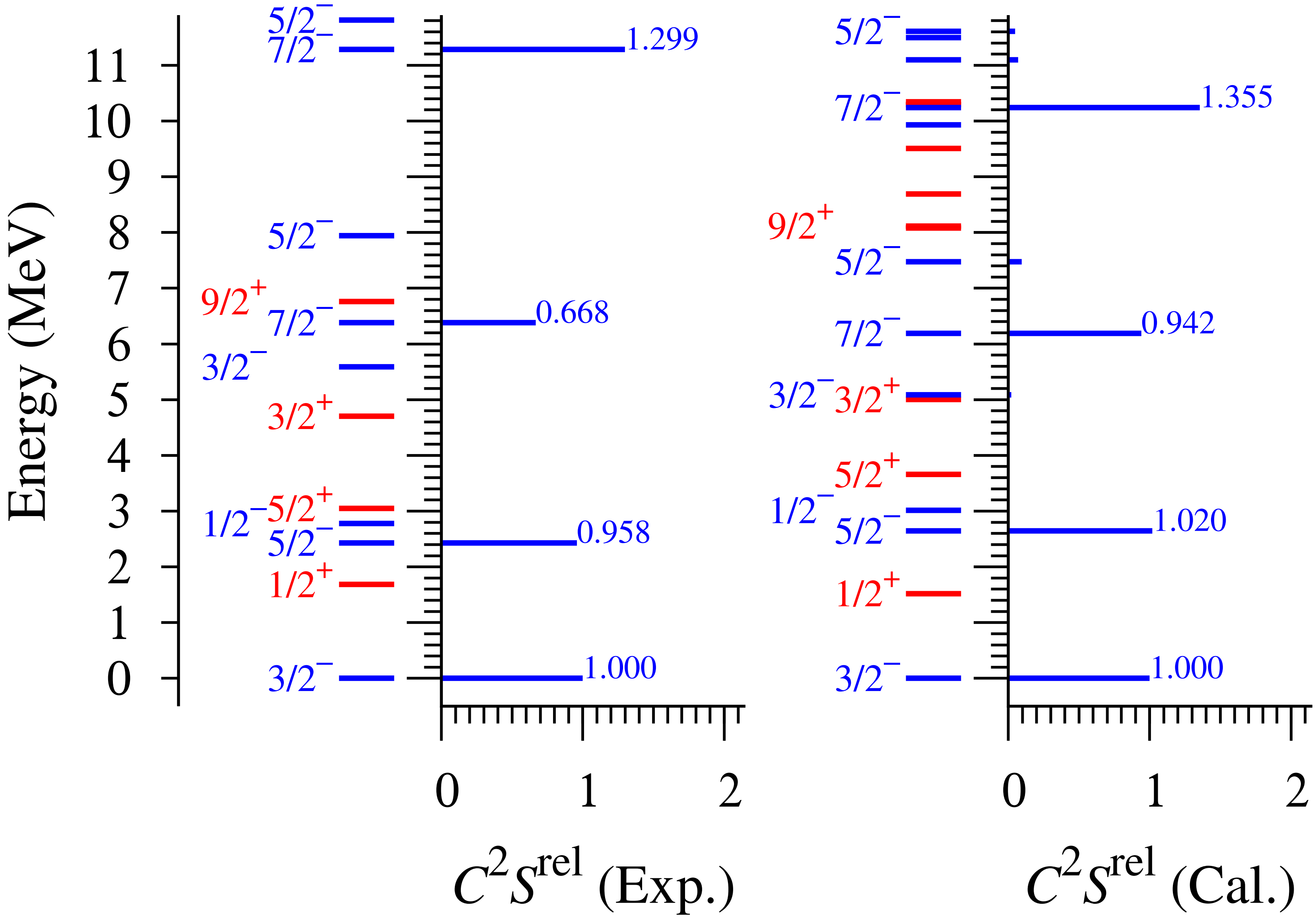
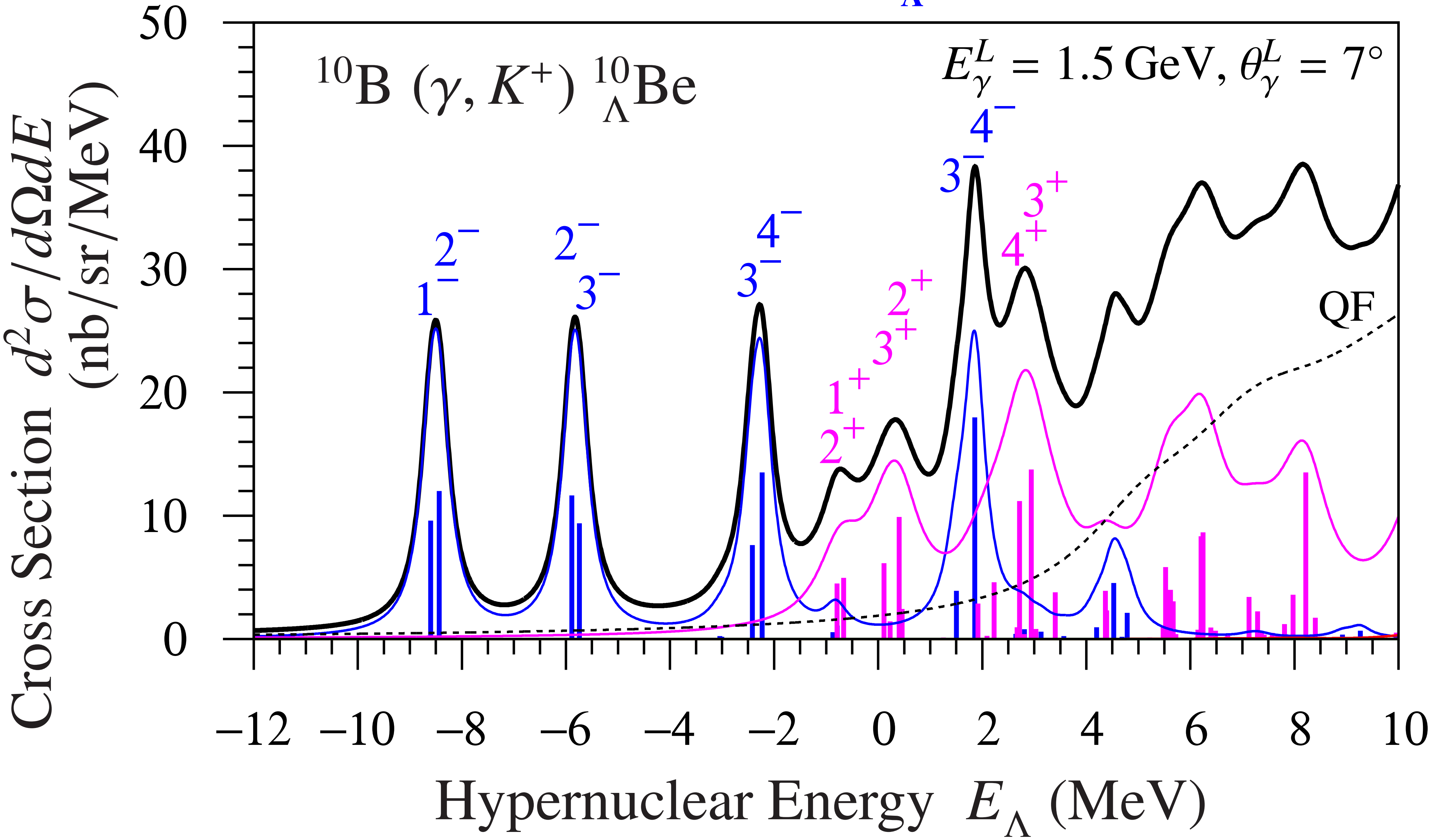
T. Gogami *et al.*, PRC93, 034314 (2016)

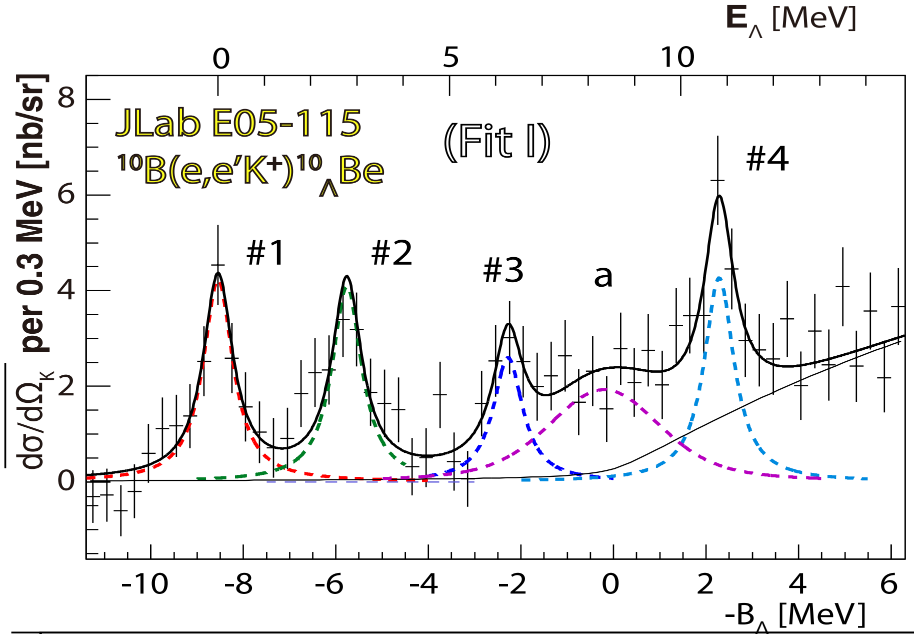
Results : Spectroscopic factors of the pickup reaction, $^{10}\mathrm{B} \rightarrow {}^{9}\mathrm{Be}$



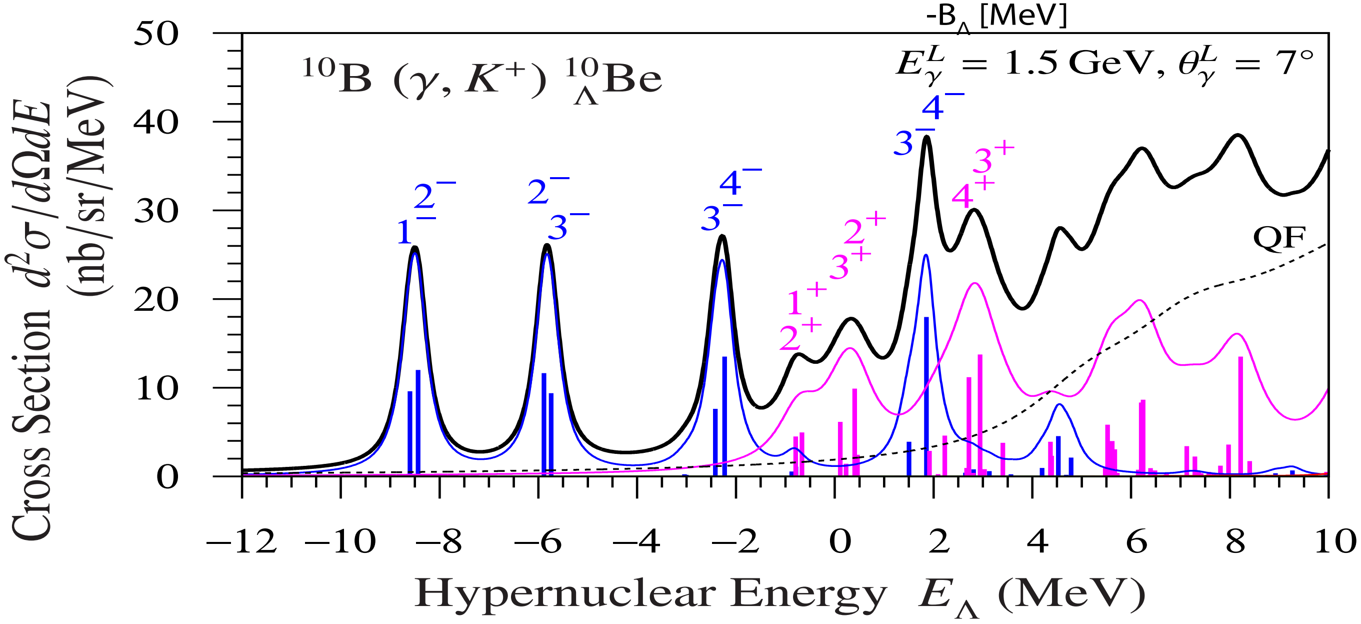
Results : Cross sections of the ${}^{10}\mathrm{B}\ (\gamma, K^+)\ {}^{10}_{\Lambda}\mathrm{Be}$ reaction (1)



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)	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

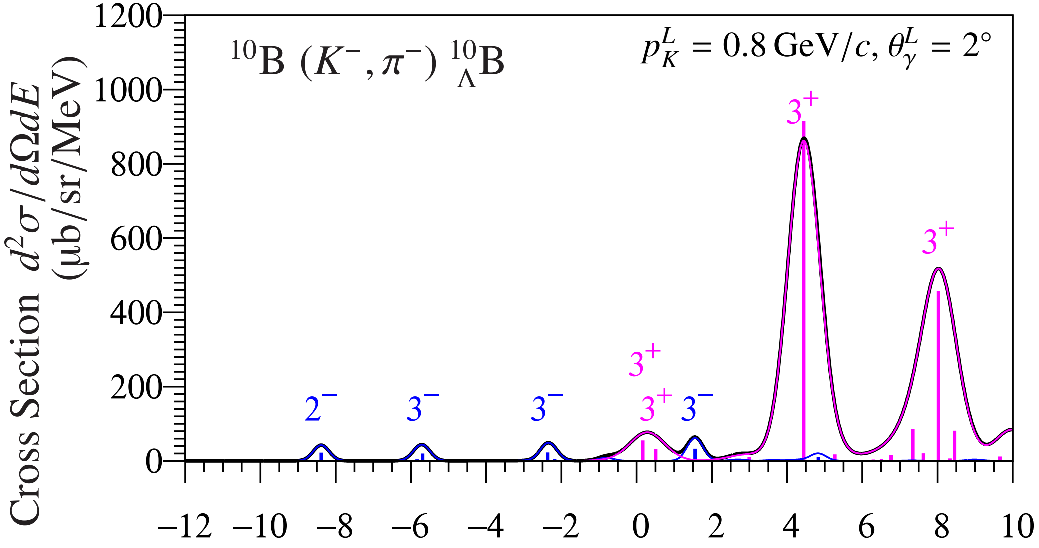
J_k	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]	
1^-	0.000	−8.600	9.609	**21.62**
2^-	0.165	−8.435	12.008	
2^-	2.712	−5.888	11.654	**21.05**
3^-	2.860	−5.740	9.391	
3^-	6.183	−2.417	7.625	**21.13**
4^-	6.370	−2.230	13.505	
$2^+(3)$	7.807	−0.793	4.495	**9.46**
$1^+(3)$	7.935	−0.665	4.968	
$3^+(2)$	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	

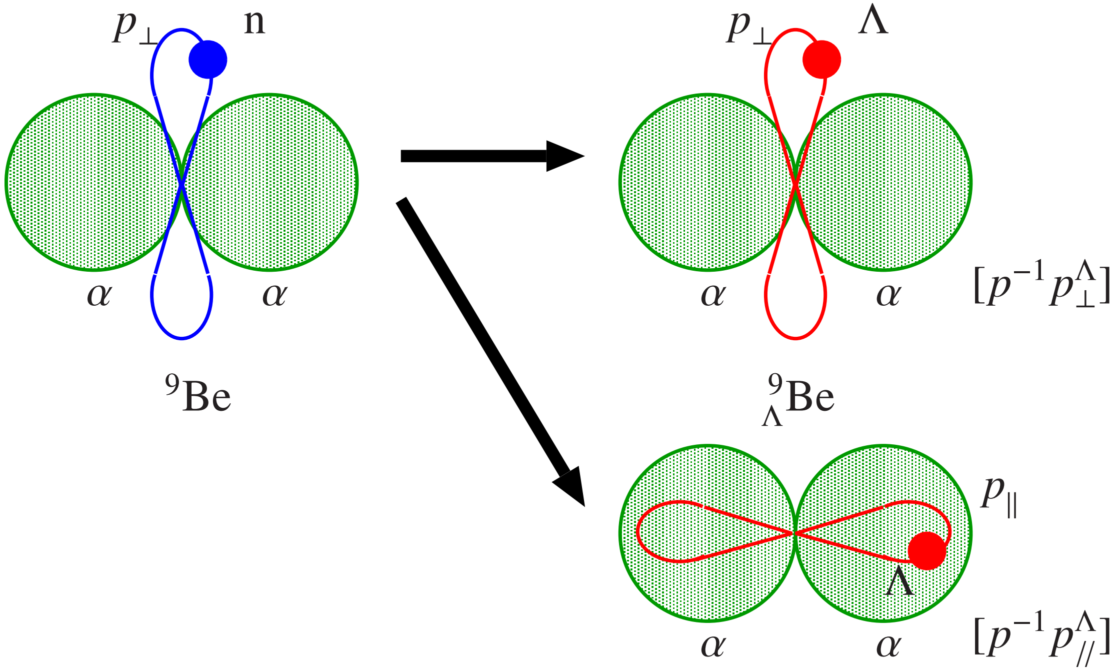
	EXP		**Fit I**
exp peak	E_x [MeV]	$-B_\Lambda$ [MeV]	$d\sigma/d\Omega$ [nb/sr]
#1	0.00	−8.55±0.07	**17.0±0.5**
#2	2.78±0.11	−5.76±0.09	**16.5±0.5**
#3	6.26±0.16	−2.28±0.14	**10.5±0.3**
#a	8.34±0.41	−0.20±0.40	**23.2±0.7**
#4	10.83±0.10	2.28±0.07	**17.2±0.5**

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

$J^\pi_n(-B_\Lambda[\text{MeV}])$ XS [nb/sr]	$[J^\pi_{\text{core}}]j^\Lambda$	$[J^\pi_{\text{core}}]j^\Lambda$	$[J^\pi_{\text{core}}]j^\Lambda$
$2^+_3(-0.739)$ 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%

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





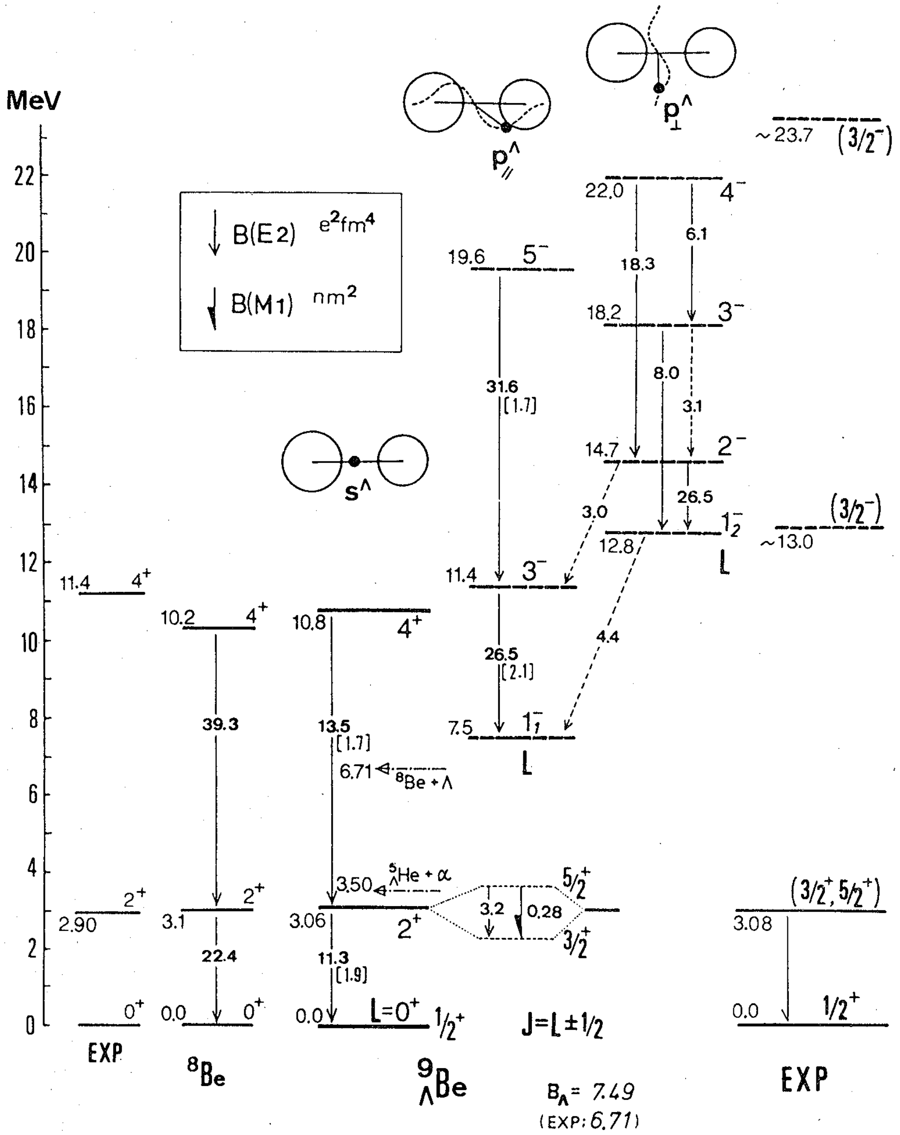
In the (K^-,π^-) reaction, the large peak at $E_\Lambda = 4.4\,\mathrm{MeV}$ is a p-substitutional state via the $p^N_{3/2} \rightarrow p^\Lambda_{3/2}$, which is strongly excited by recoilless reaction.

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.

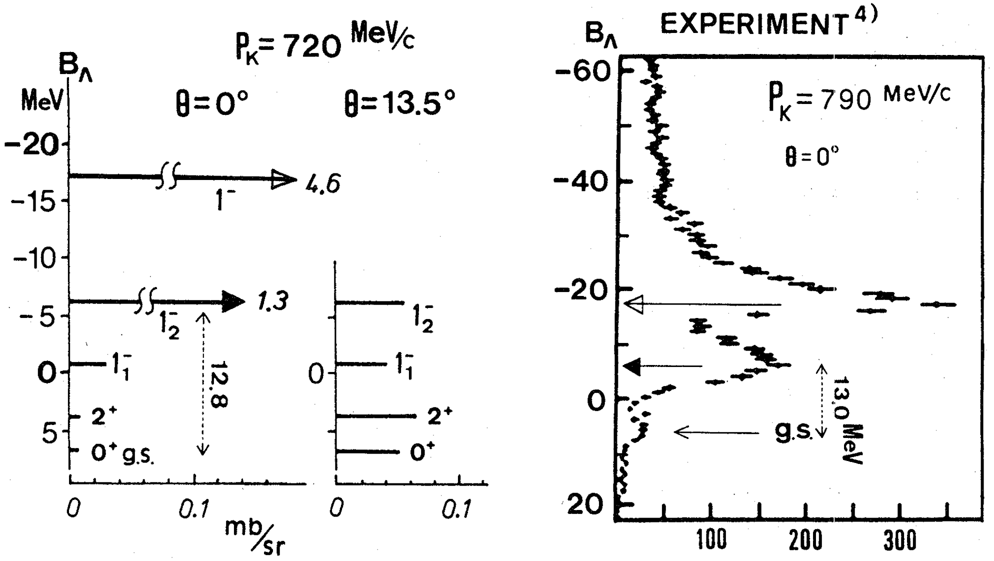
The large peak at $E_\Lambda = 4.4\,\mathrm{MeV}$ in $^{10}_{\Lambda}\mathrm{Be}$ corresponds to the $[p^{-1}p^{\Lambda}_{\perp}]$ state in $^{9}_{\Lambda}\mathrm{Be}$ ($^9\mathrm{Be}$ analog state).

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

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



$^{9}\mathrm{Be}\,(K^-,\pi^-)\,^{9}_{\Lambda}\mathrm{Be}$

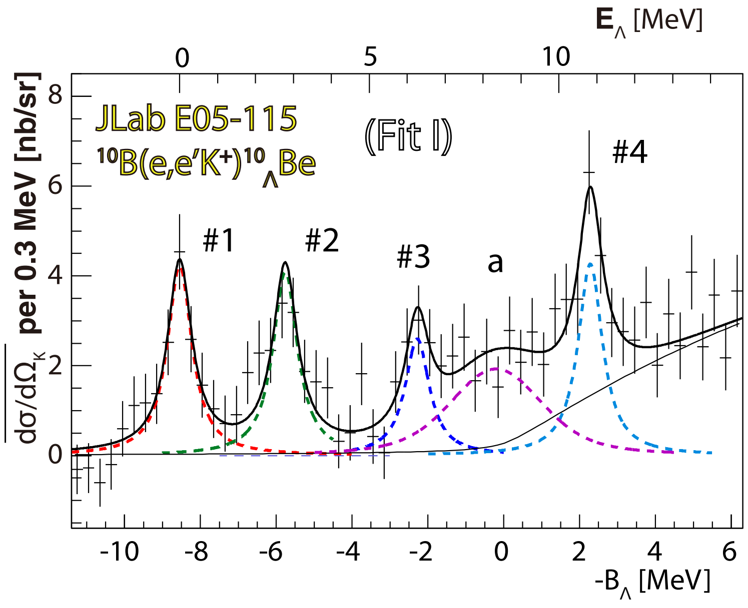


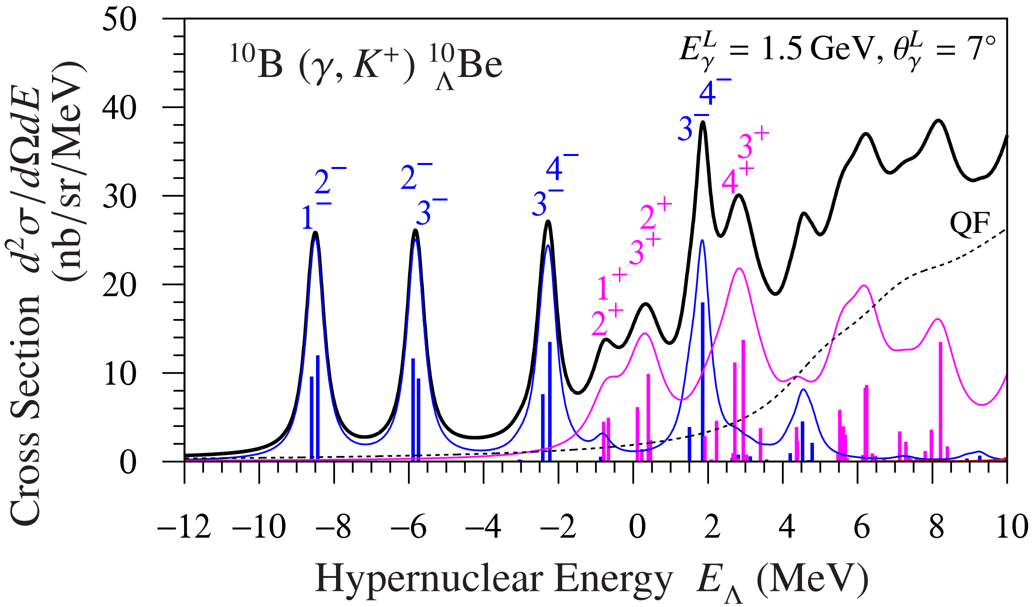
T. Motoba *et al.*, PTPS81, 42 (1985)

R. Bertini *et al.* (H-S-S Collaboration), NPA368, 365 (1981)

Summary

We have calculated the cross sections in $^{10}_{\Lambda}$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.**
- **The new bump in $^{10}_{\Lambda}$Be corresponds to the $[p^{-1} p^{\Lambda}_{//}]$ state in $^{9}_{\Lambda}$Be.**