Hypernuclear structure with antisymmetrized molecular dynamics

Structure of Be hypernuclei ($^{10}{}_{\Lambda}$Be, $^{11}{}_{\Lambda}$Be and $^{12}{}_{\Lambda}$Be)

Based on

M. Isaka and M. Kimura, PRC**92**, 044326 (2015)

H. Homma, M. Isaka and M. Kimura, PRC**91**, 014314(2015)

Effects of core structure on B_{Λ} values: many-body force effects/density dependence

Based on

M. Isaka, Y. Yamamoto and Th.A. Rijken, PRC**94,** 044310(2016)

M. Isaka, Y. Yamamoto and Th.A. Rijken, PRC in print

Masahiro Isaka

(RCNP, Osaka University)

Grand challenges of hypernuclear physics

Interaction: To understand baryon-baryon interaction

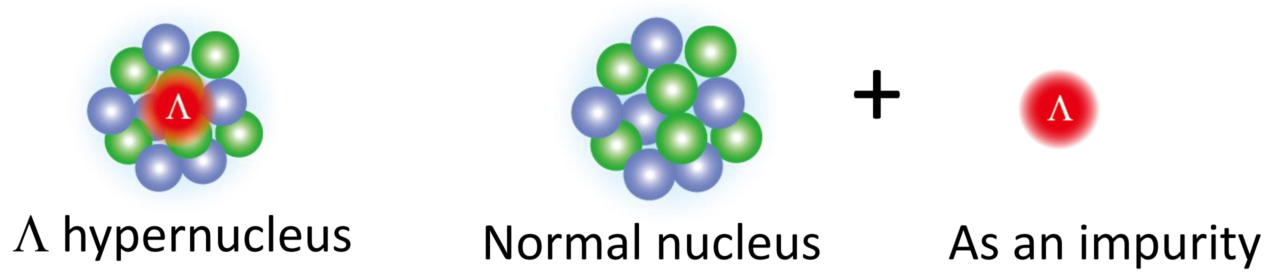
- **2 body interaction between baryons (nucleon, hyperon)**
  - hyperon-nucleon (YN)
  - hyperon-hyperon (YY)

A major issue in hypernuclear physics

Structure: To understand many-body system of nucleons and hyperon

- **Structure changes by hyperon(s)**
  - No Pauli exclusion between N and Y
  - YN interaction is different from NN

"Hyperon as an impurity in nuclei"



Today's talk: "Structure change by a Λ particle"

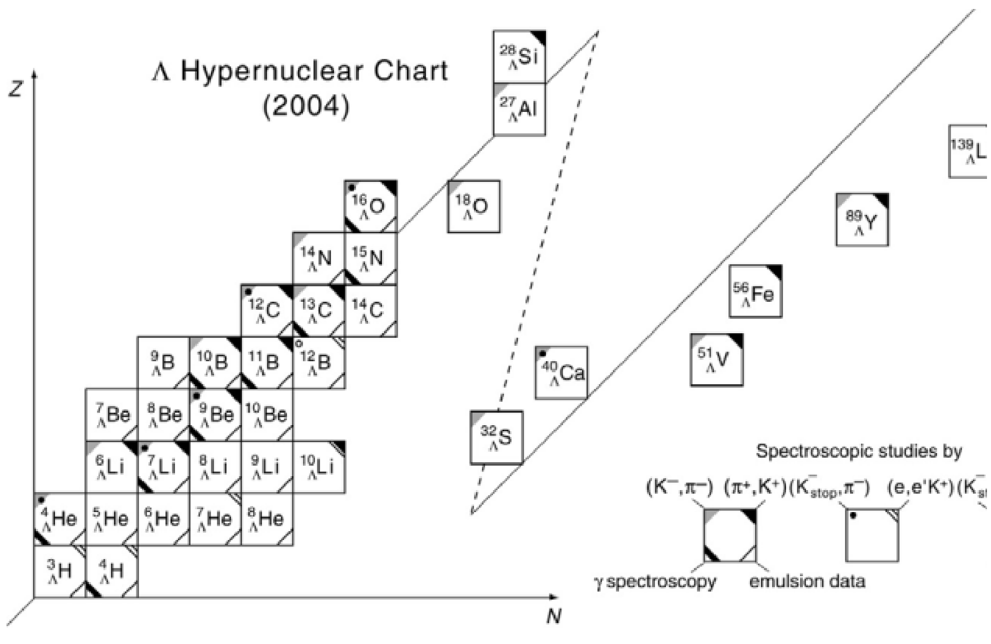
Interaction: recent achievements

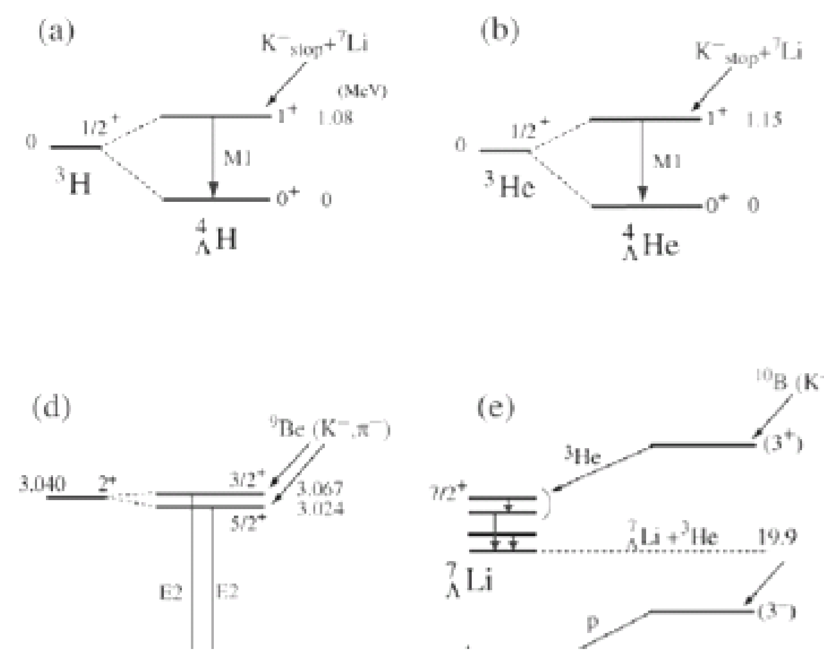
Λ hypernuclei observed so far

- **Concentrated in light Λ hypernuclei with A ≲ 16**
  - Structure study based on accurate calc. of few-body problems
  - Increases of experimental information

Hiyama & Yamada, PPNP **63** (2009) 339.
Hashimoto, & Tamura, PPNP **57** (2006), 564.

→
- **Increasing knowledge of ΛN two-body interaction**
- **Development of ΛN interaction models**





Figs: taken from Hashimoto and Tamura, PPNP **57** (2006), 564.

Interaction: recent achievements

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- **Increasing knowledge of ΛN two-body interaction**
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Developments of effective interactions

In this study,

G-matrix interaction derived from Nijmegen potential (YNG)

- Nijmegen potential: a meson exchange model
- G-matrix calculation takes into account medium effects

YNG interaction has density (Fermi momentum k_F) dependence coming from ΛN-ΣN coupling effects

k_F can be calculated from density
e.g. Averaged Density Approximation (ADA)

$$k_F = \left(\frac{3\pi^2\langle\rho\rangle}{2}\right)^{1/3}, \quad \langle\rho\rangle = \int dr^3 \rho_N(\mathbf{r})\rho_\Lambda(\mathbf{r})$$

Y. Yamamoto, T. Motoba and Th.A. Rijken, PTPS185(2010)72.

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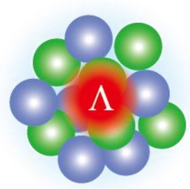
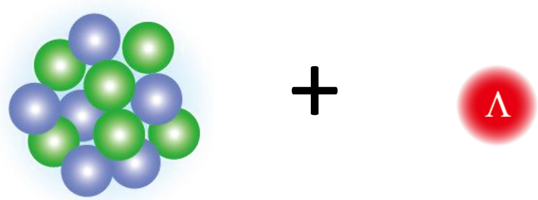


Λ hypernucleus



Normal nucleus

As an impurity

Today's talk: "Structure change by a Λ particle"

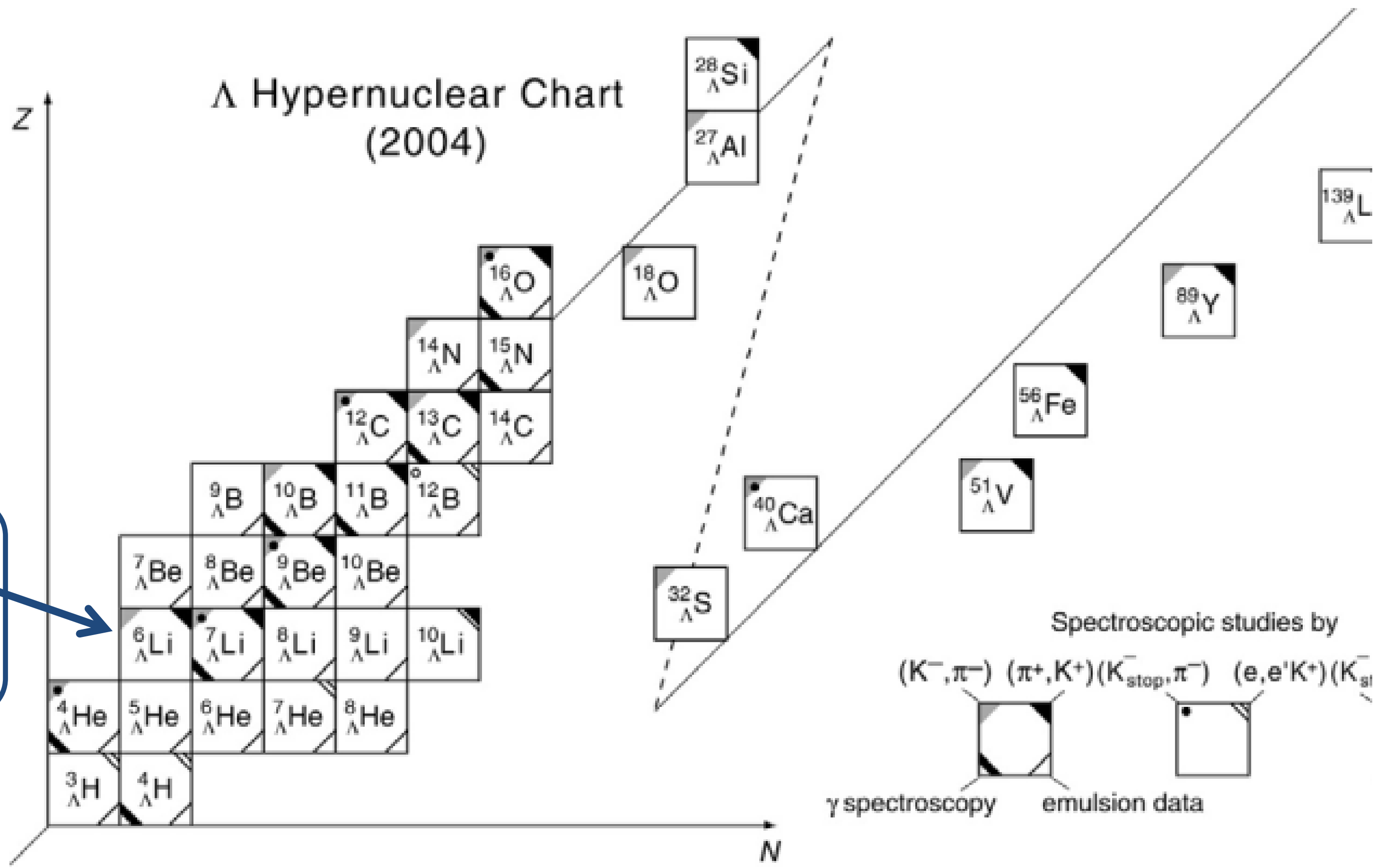
Structure of Λ hypernuclei

Λ hypernuclei observed so far

- Concentrated in light Λ hypernuclei
- Most of them have well pronounced cluster structure

Light Λ hypernuclei

Developed cluster



Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

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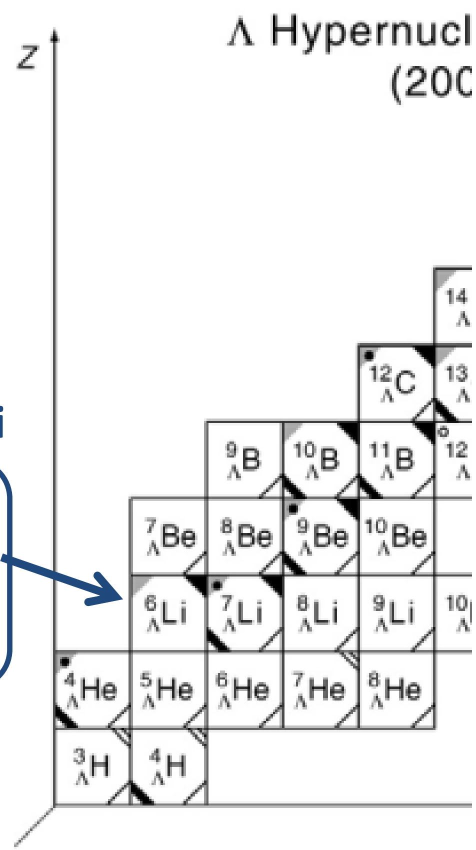


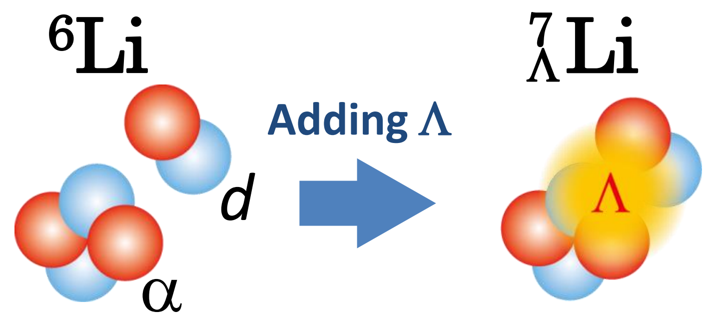
Light Λ hypernuclei

Developed cluster

Changes of cluster structure

Example: ${}^{7}_{\Lambda}\mathrm{Li}$

T. Motoba, et al., PTP **70**,189 (1983)
E. Hiyama, et al., PRC **59** (1999), 2351.
K. Tanida, et al., PRL **86** (2001), 1982.



- Λ reduces inter-cluster distance between α + d
- Confirmed through B(E2) reduction

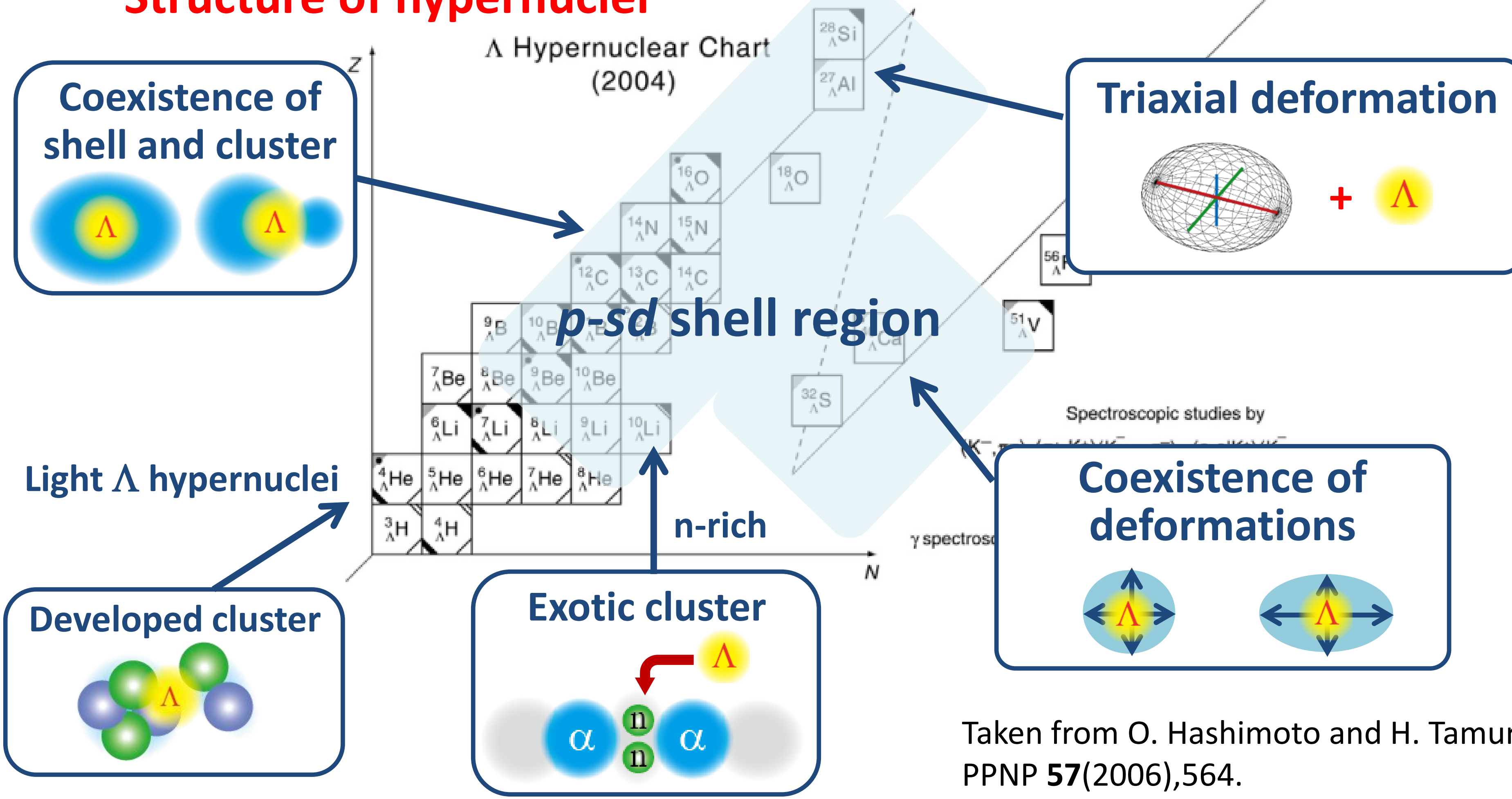
Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Toward heavier and exotic Λ hypernuclei

Experiments at J-PARC and JLab etc.

- **Hypernuclear chart will be extended to heavier regions**

"Structure of hypernuclei"



Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Structure study of such hypernuclei becomes one of interesting topics

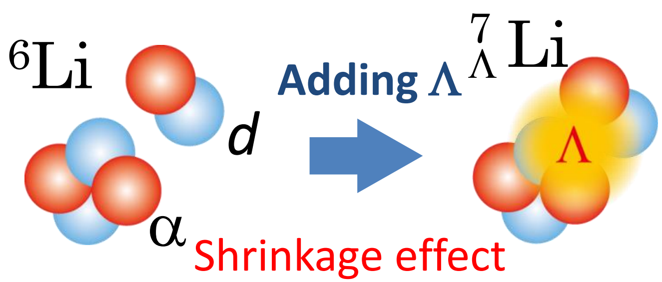
Structure in hypernuclei: impurity effects

What is interesting and important?

◆ Change of cluster structure

- **"How does a Λ particle modify cluster states?"**

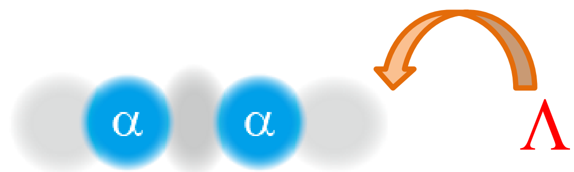
Ex: ${}^{7}_{\Lambda}\mathrm{Li}$



Experiment: Tanida, et al., PRL **86**, 1982(2001).

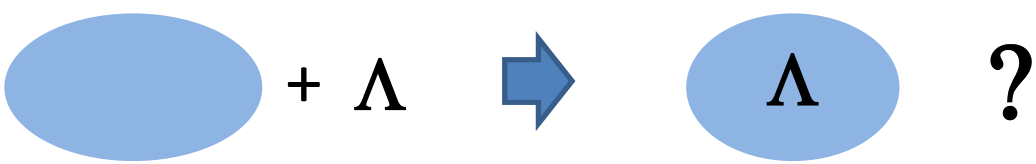
How about other cluster states?

Dependence on degrees of clustering



◆ Deformation changes by Λ

- **"How do nuclear deformations change if Λ particle is added?"**



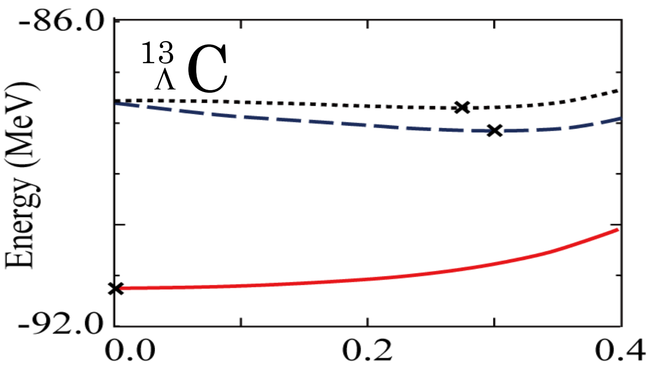
etc.

Deformation change by Λ in *s*-orbit

- **Many authors predict the deformation change by Λ in *s*-orbit**

AMD

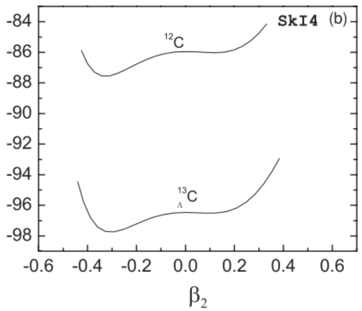
M.Isaka, *et al*., PRC**83**, 044323('11)

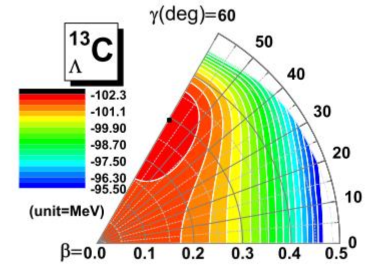


Skyrme-Hartree-Fock (SHF)

X.R. Zhou, et al., PRC**76**, 034312('07)

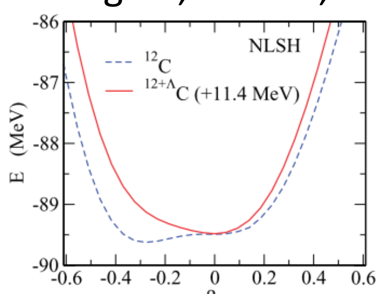
J.W. Cui, X.R. Zhou, H.J. Schulze, PRC**91**,054306('15)



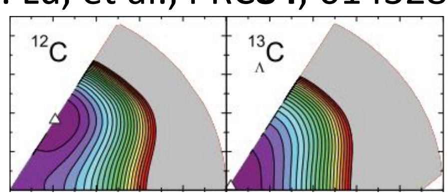


Relativistic mean-field (RMF)

Win and Hagino, PR C**78**, 054311('08)

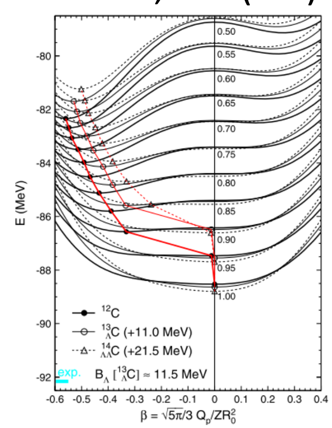


B.N. Lu, et al., PRC**84**, 014328 ('11)



RMF & SHF

H. J. Schulze, et al., PTP**123**, 569('10)



Deformations/level structure with beyond-mean-field

J.W. Cui, X.R. Zhou, H.J. Schulze, PRC**91**,054306('15)

H. Mei, K. Hagino, J.M. Yao, T. Motoba, PRC91, 064305('15)

etc.

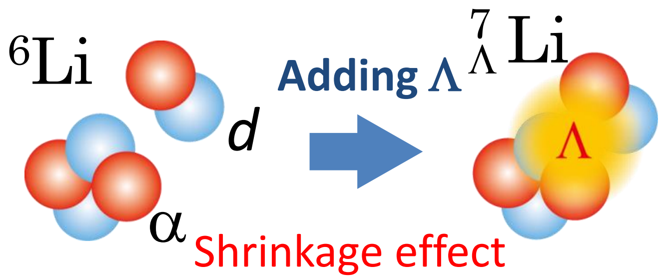
Structure in hypernuclei: impurity effects

What is interesting and important?

◆ **Change of cluster structure**

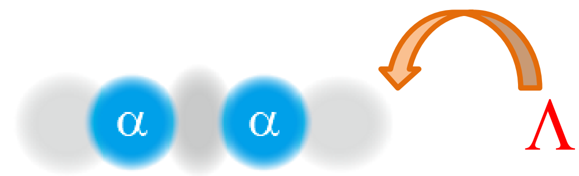
- **"How does a Λ particle modify cluster states?"**

Ex: $^{7}{}_{\Lambda}\mathrm{Li}$



Experiment: Tanida, et al., PRL **86**, 1982(2001).

How about other cluster states?
Dependence on degrees of clustering



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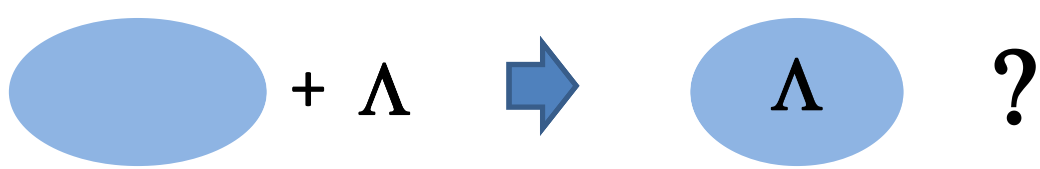


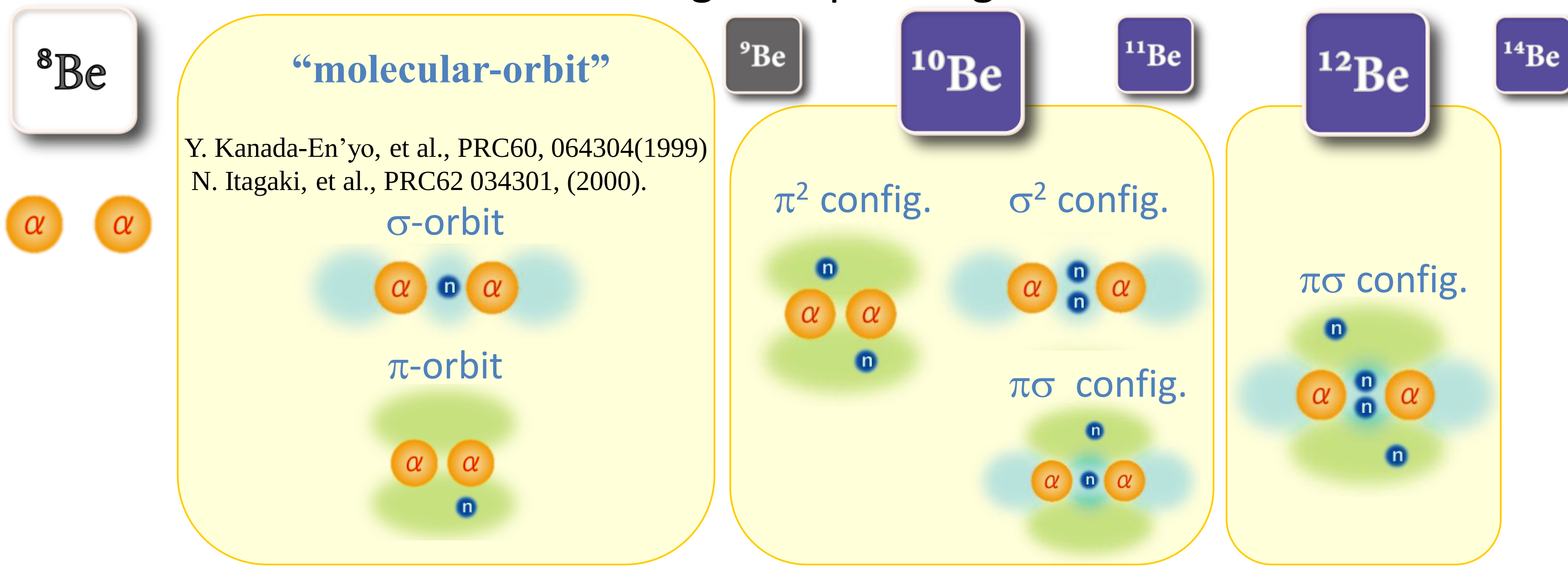
etc.

Today's talk: "change of cluster structure"
Example: Be hypernuclei

Structure of neutron-rich nuclei

Ex.) Be isotopes

- **Exotic cluster structure exists in the ground state regions**
- **Be isotopes have a 2α cluster structure**
  - 2α cluster structure is changed depending on the neutron number



Today's talk: "change of cluster structure"
changes of 2α cluster structure by Λ and dependence on states
Example: $^{10}_{\Lambda}$Be, $^{11}_{\Lambda}$Be, and $^{12}_{\Lambda}$Be

Theoretical Framework: HyperAMD

M.Isaka, *et al.*, PRC**83**(2011) 044323
M. Isaka, *et al.*, PRC**83**(2011) 054304

We extended the AMD to hypernuclei

HyperAMD (Antisymmetrized Molecular Dynamics for hypernuclei)

◆Hamiltonian

$$\hat{H} = \hat{T}_N + \hat{V}_{NN} + \hat{T}_\Lambda + \hat{V}_{\Lambda N} - \hat{T}_g$$

NN : Gogny D1S

ΛN : YNG interactions (ESC08c, NSC97f, NF)

◆Wave function

- **Nucleon part : Slater determinant**

  Spatial part of single particle w.f. is described as Gaussian packet

$$\varphi_N(\vec{r}) = \frac{1}{\sqrt{A!}} \det\left[\varphi_i(\vec{r}_j)\right]$$

$$\varphi_i(r) \propto \exp\left[-\sum_{\sigma=x,y,z} \nu_\sigma (r - Z_i)_\sigma^2\right] \chi_i \eta_i \qquad \chi_i = \alpha_i \chi_\uparrow + \beta_i \chi_\downarrow$$

- **Single-particle w.f. of Λ hyperon:**

  Superposition of Gaussian packets

$$\varphi_\Lambda(r) = \sum_m c_m \varphi_m(r)$$

$$\varphi_m(r) \propto \exp\left[-\sum_{\sigma=x,y,z} \mu\nu_\sigma (r - z_m)_\sigma^2\right] \chi_m \qquad \chi_m = a_m \chi_\uparrow + b_m \chi_\downarrow$$

- **Total w.f. :**

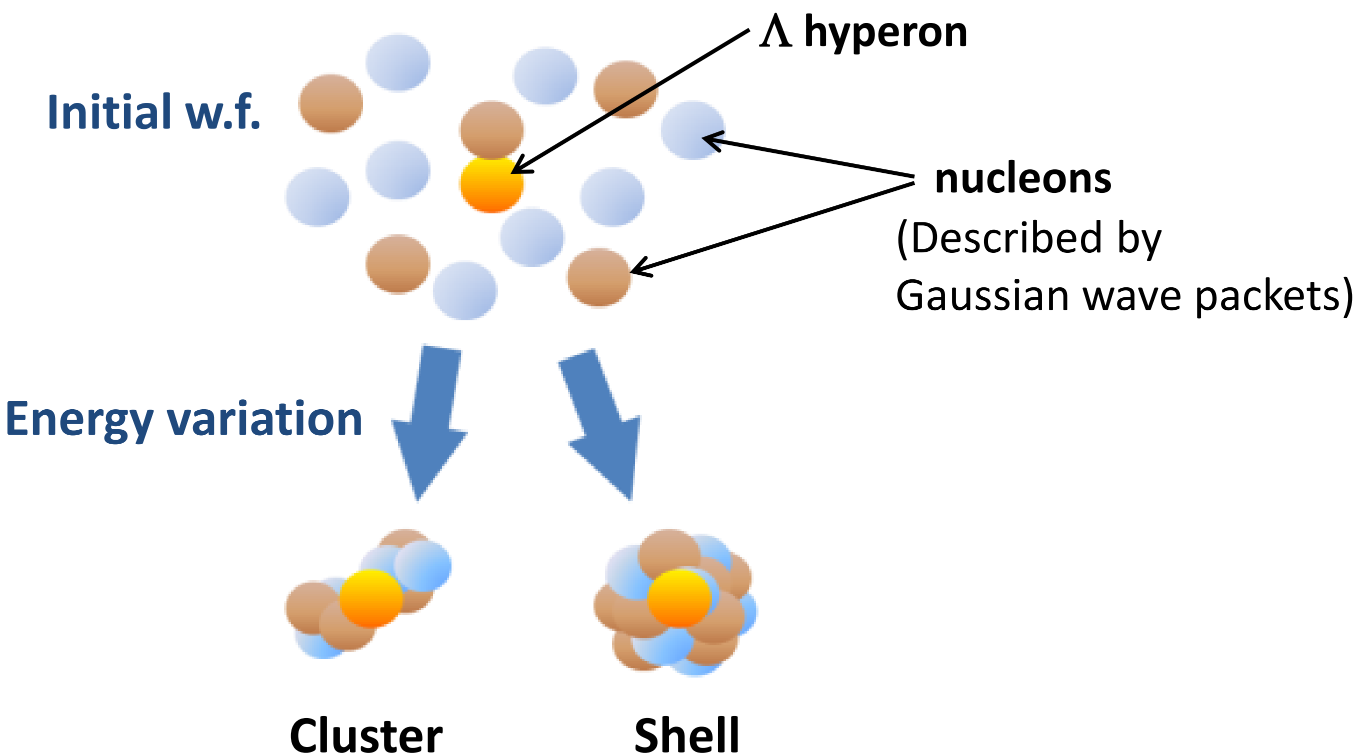
$$\psi(\vec{r}) = \sum_m c_m \varphi_m(r_\Lambda) \otimes \frac{1}{\sqrt{A!}} \det\left[\varphi_i(\vec{r}_j)\right]$$

Theoretical framework: HyperAMD

◆ Procedure of the calculation

Variational Calculation

- Imaginary time development method $$\frac{dX_i}{dt} = \frac{\kappa}{\hbar}\frac{\partial H^{\pm}}{\partial X_i^*} \qquad \kappa < 0$$
- Variational parameters: $X_i = Z_i, z_i, \alpha_i, \beta_i, a_i, b_i, \nu_i, c_i$



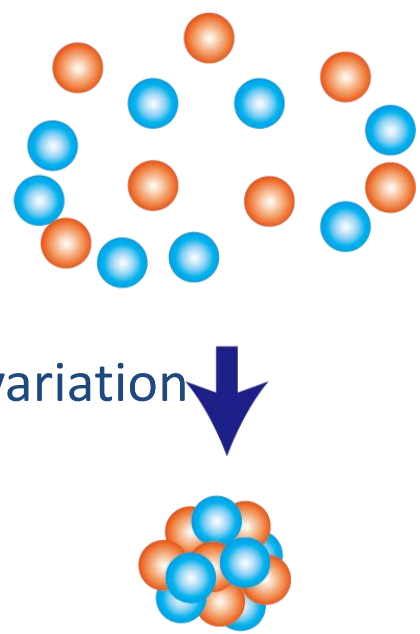
Actual calculation of HyperAMD

M.Isaka, *et al*., PRC**83**(2011) 044323
M. Isaka, *et al*., PRC**83**(2011) 054304

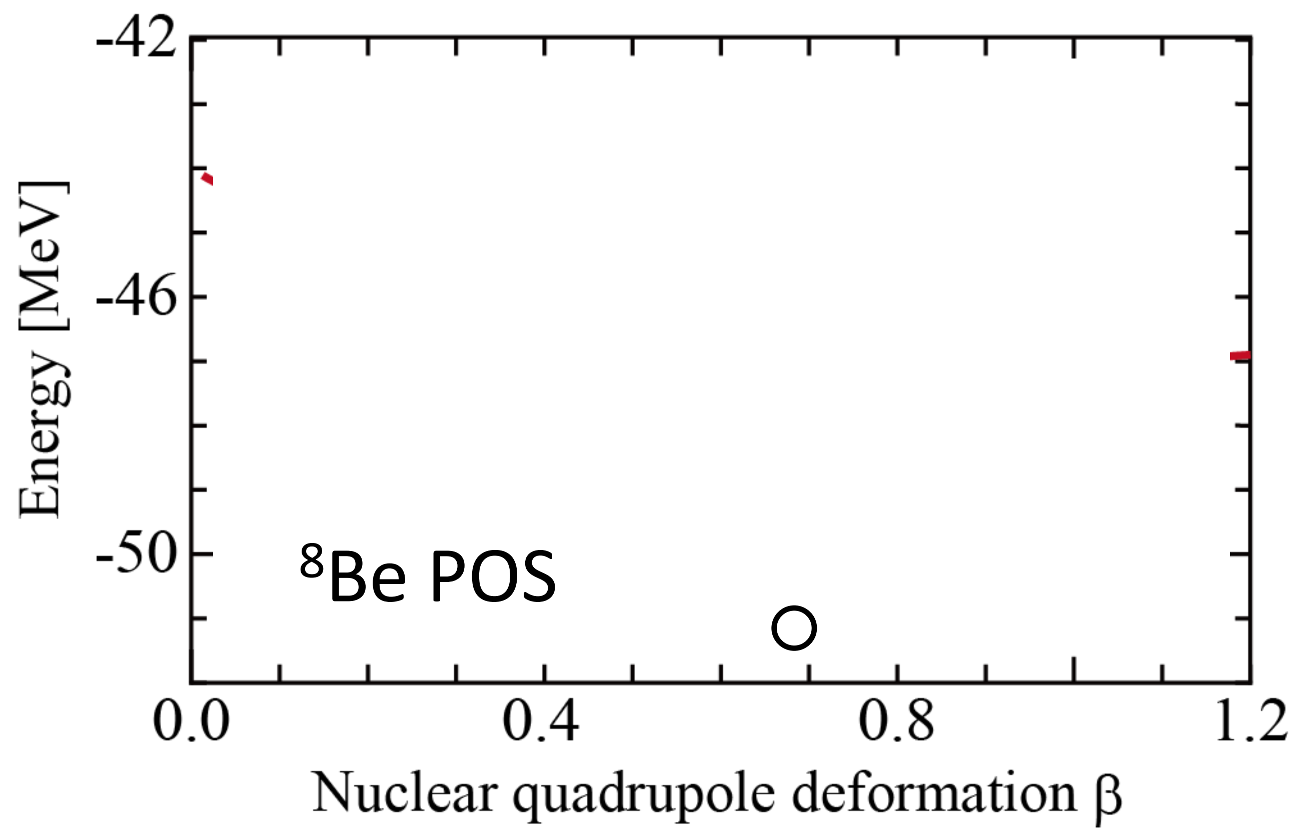
Energy variation with constraint on nuclear quadrupole deformation

Ex.) ^{8}Be

Initial w.f.



w/o constraint on β



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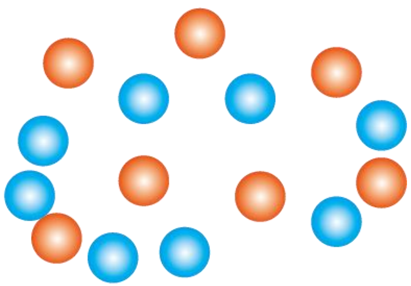
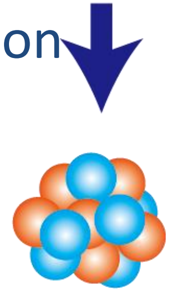
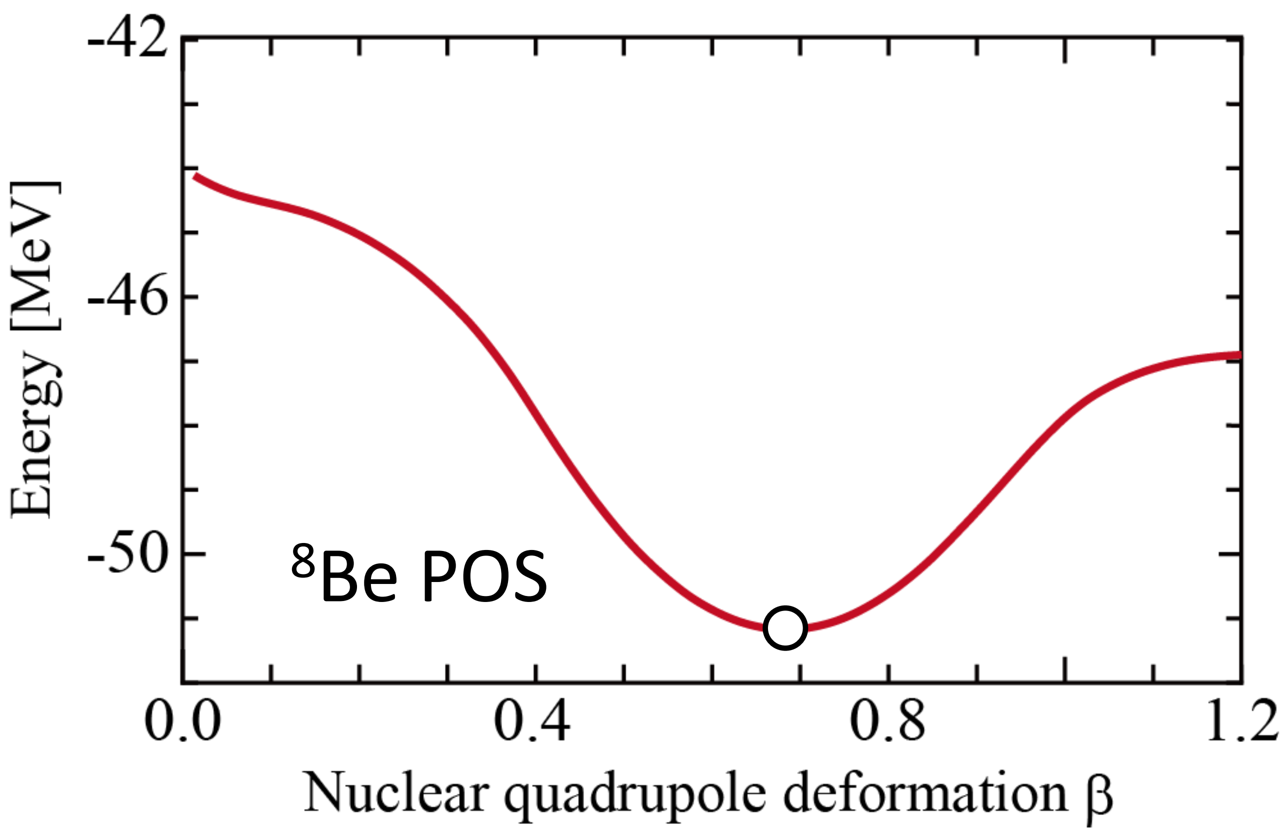


variation



with constraint on β



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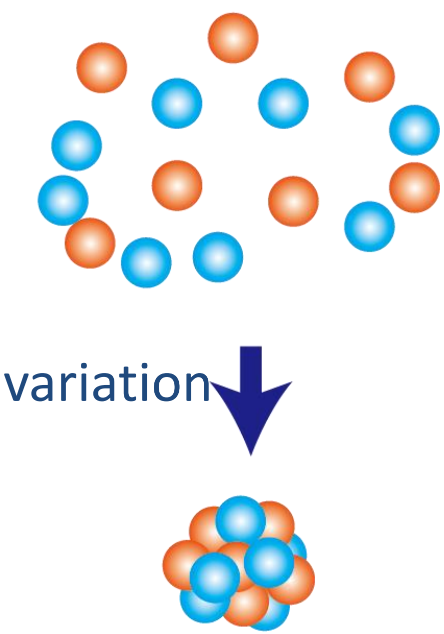

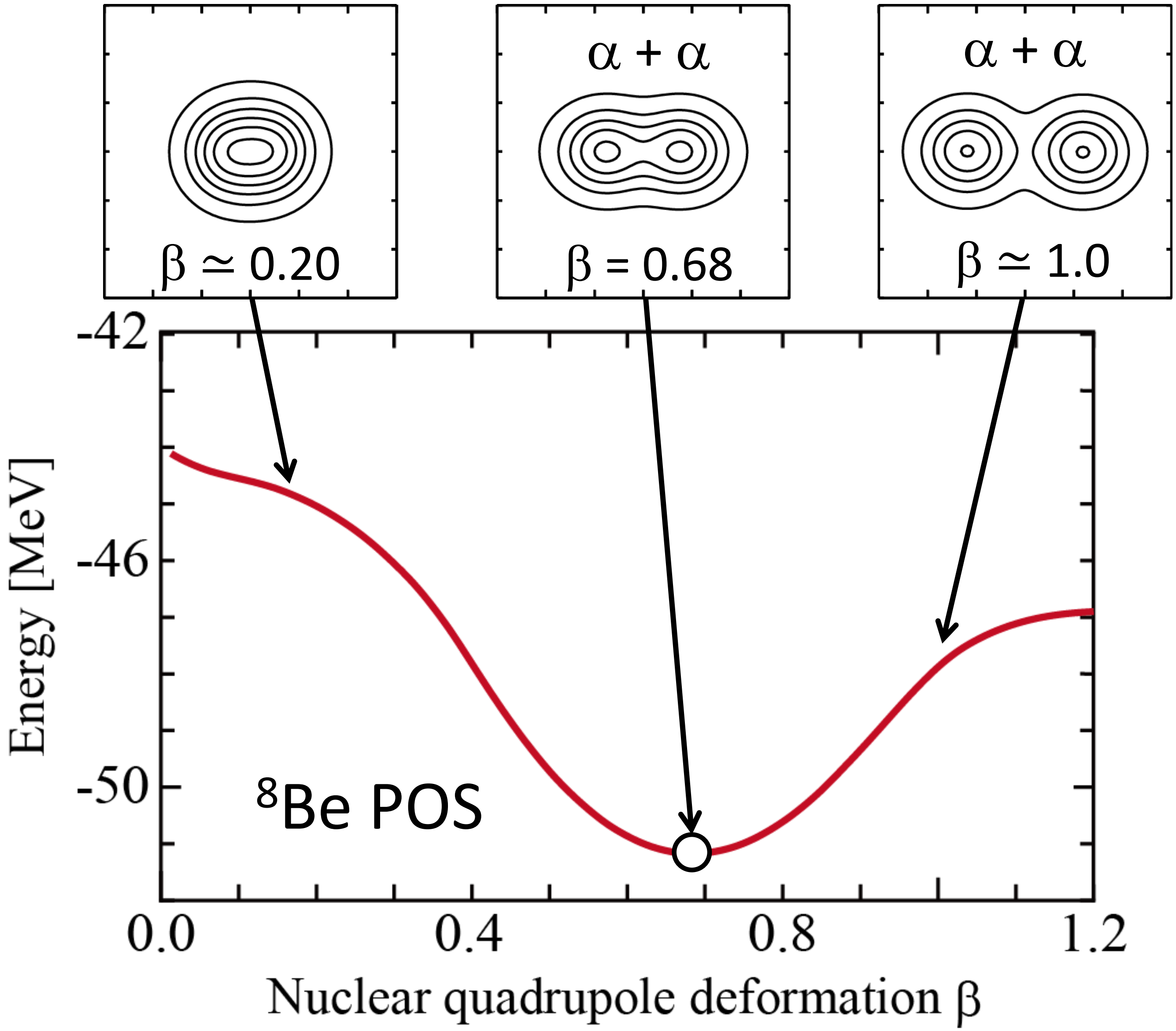

Actual calculation of HyperAMD

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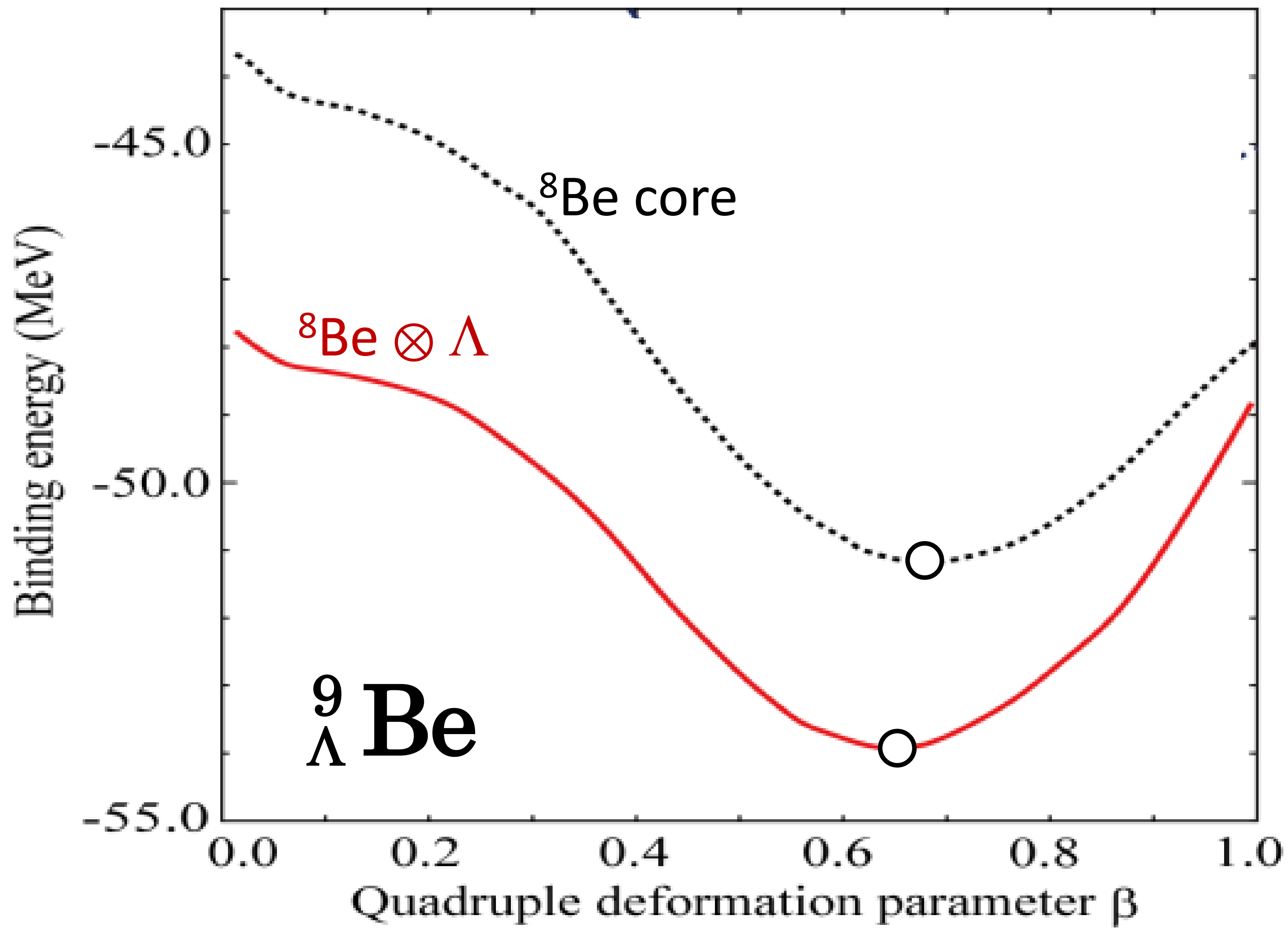
◆ For hypernuclei



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Angular Momentum Projection

$$\left|\Phi_K^s; JM\right\rangle = \int d\Omega D_{MK}^{J*}(\Omega) R(\Omega) \left|\Phi^{s+}\right\rangle$$

Generator Coordinate Method(GCM)

- Superposition of the w.f. with different configuration
- Diagonalization of $H_{sK,s'K'}^{J\pm}$ and $N_{sK,s'K'}^{J\pm}$

$$H_{sK,s'K'}^{J\pm} = \left\langle \Phi_K^s; J^{\pm}M \middle| \hat{H} \middle| \Phi_{K'}^{s'}; J^{\pm}M \right\rangle$$

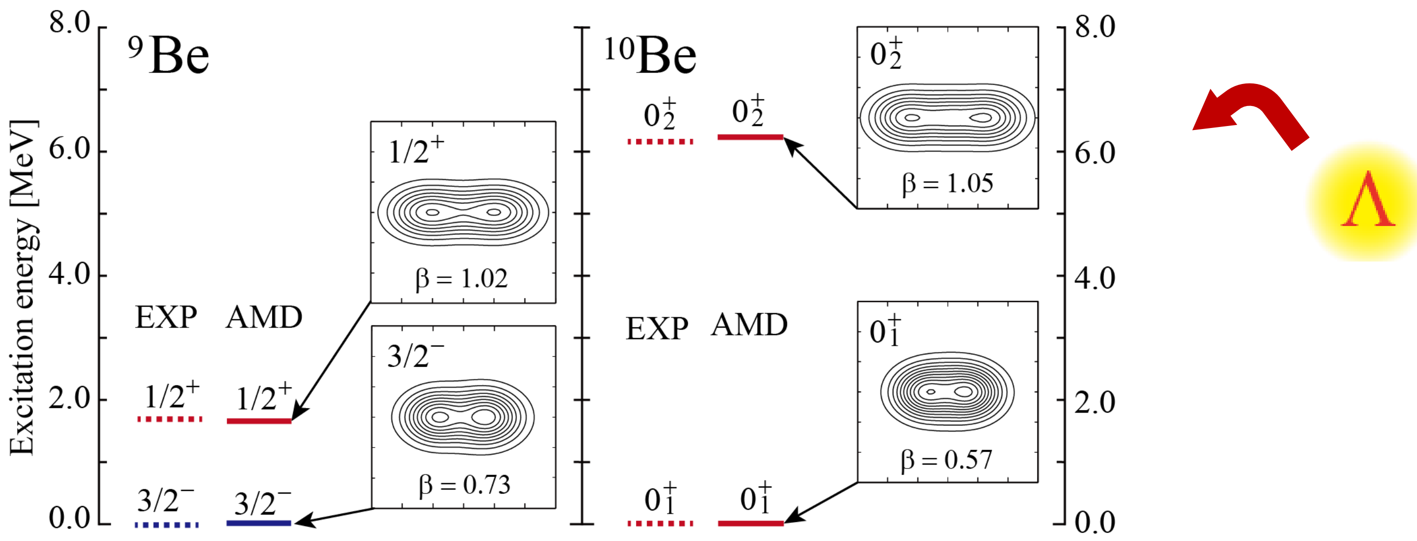
$$N_{sK,s'K'}^{J\pm} = \left\langle \Phi_K^s; J^{\pm}M \middle| \Phi_{K'}^{s'}; J^{\pm}M \right\rangle$$

$$\left|\Psi^{J\pm M}\right\rangle = \sum_{sK} g_{sK} \left|\Phi_K^s; J^{\pm}M\right\rangle$$

1. Change of cluster structure

How does a Λ modify 2α clustering in Be ?

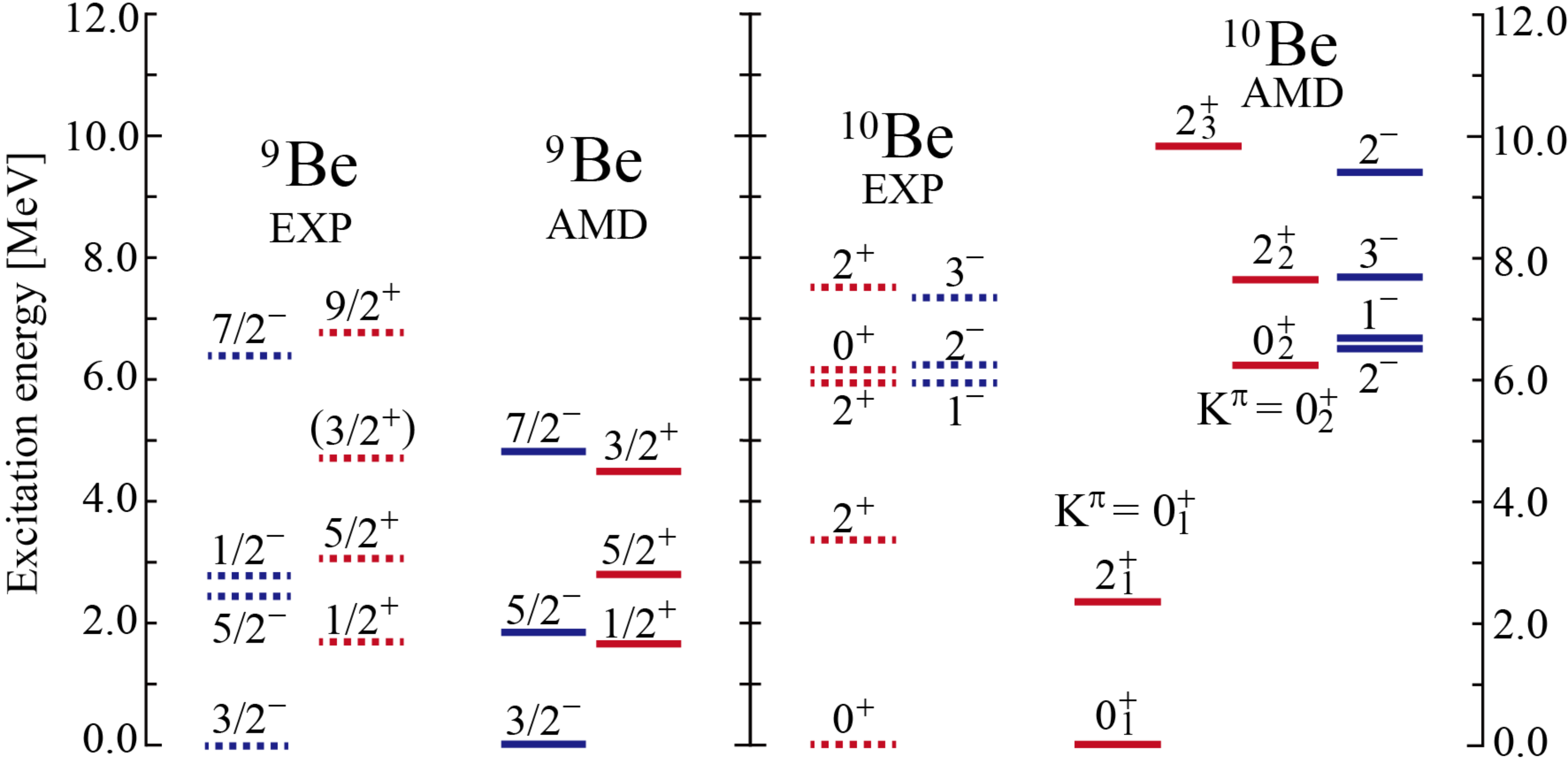
Examples: $^{10}{}_{\Lambda}$Be, $^{11}{}_{\Lambda}$Be and $^{12}{}_{\Lambda}$Be



- Degrees of structure changes
- Dependence of structure changes on core structure

M. Isaka and M. Kimura, PRC**92**, 044326 (2015)
H. Homma, M. Isaka and M. Kimura, PRC**91**, 014314(2015)

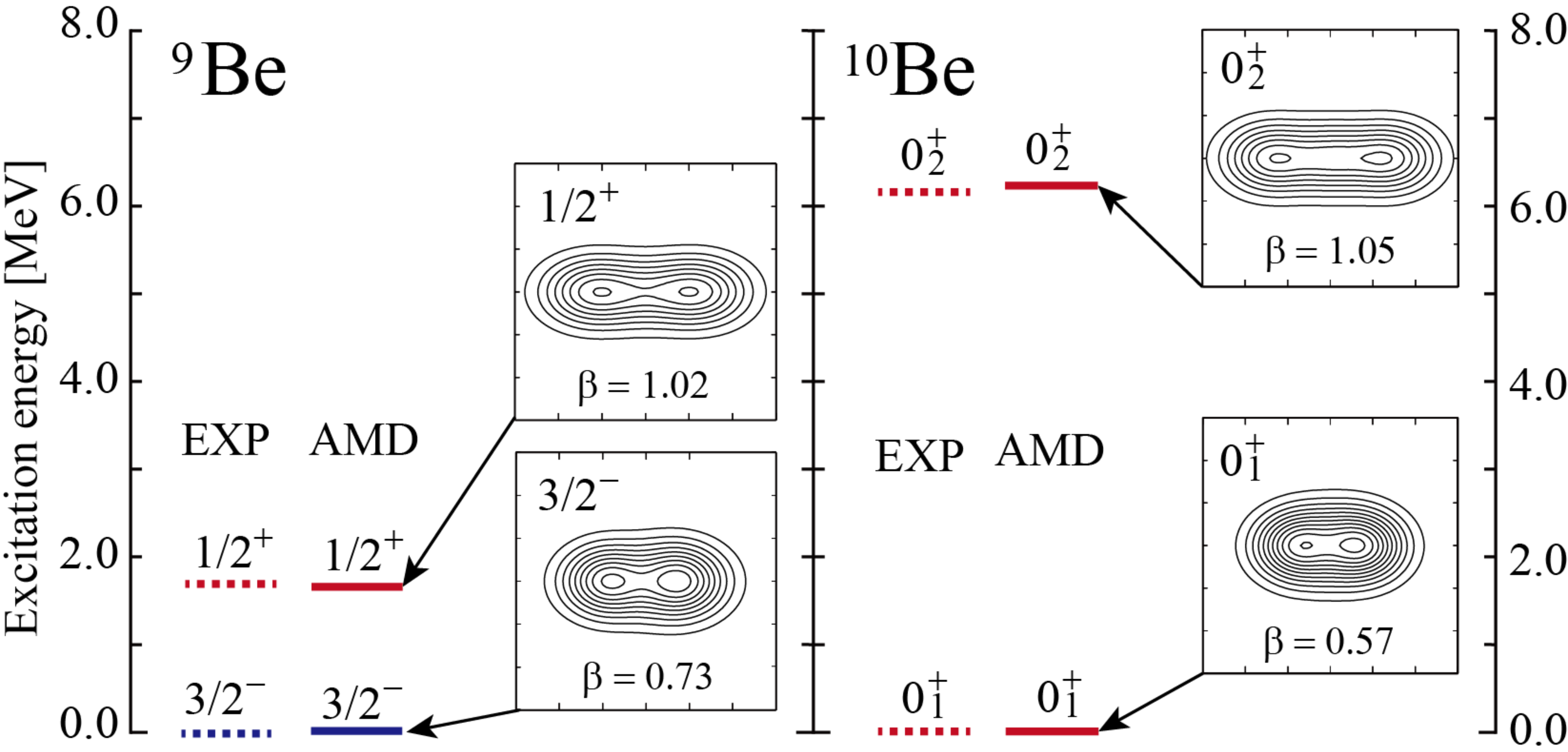
Structure of ^{9}Be and ^{10}Be



Strength of LS force is weakened by 5% (strengthen by 17%) in ^{9}Be (^{10}Be) to reproduce observed Ex($1/2^+$) (Ex(0^+_2))

Structure of ^{9}Be and ^{10}Be

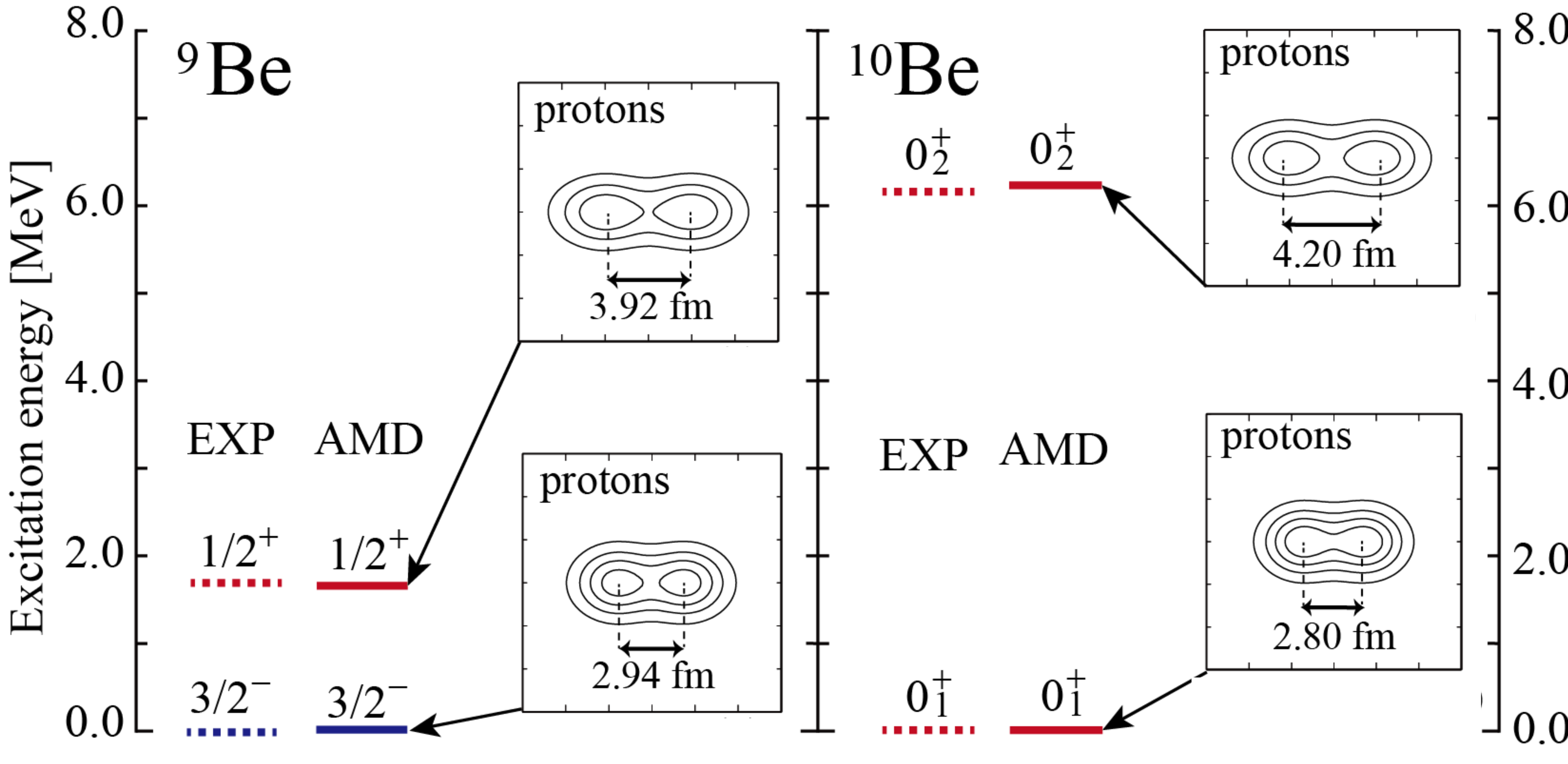
We focus on $3/2^-$ and $1/2^+$ states of ^{9}Be and 0^+_1 and 0^+_2 states of ^{10}Be with different degrees of 2α clustering



Degrees of 2α clustering is dependent on states

Structure of ^{9}Be and ^{10}Be

We focus on $3/2^-$ and $1/2^+$ states of ^{9}Be and 0^+_1 and 0^+_2 states of ^{10}Be with different degrees of 2α clustering



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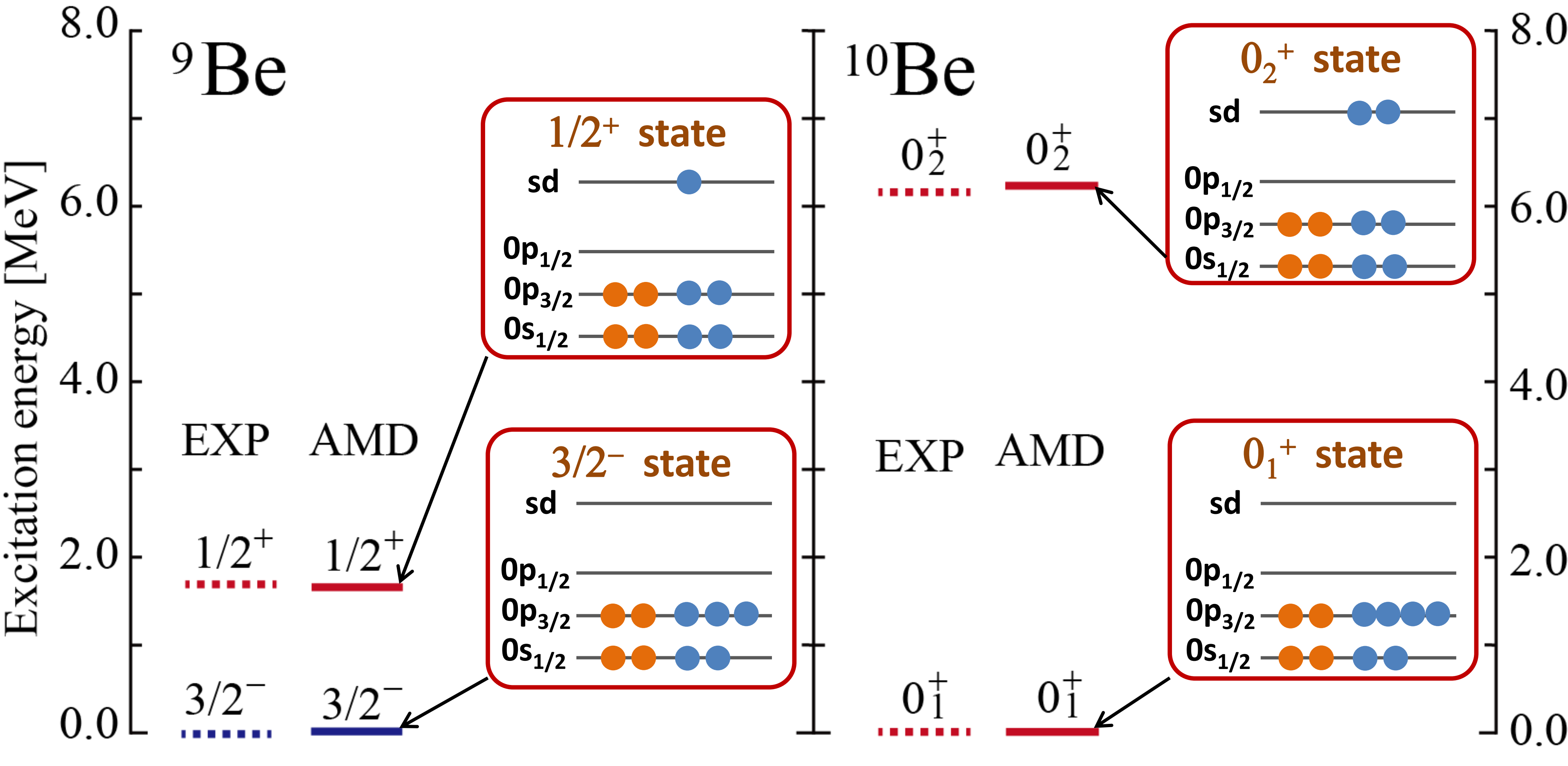

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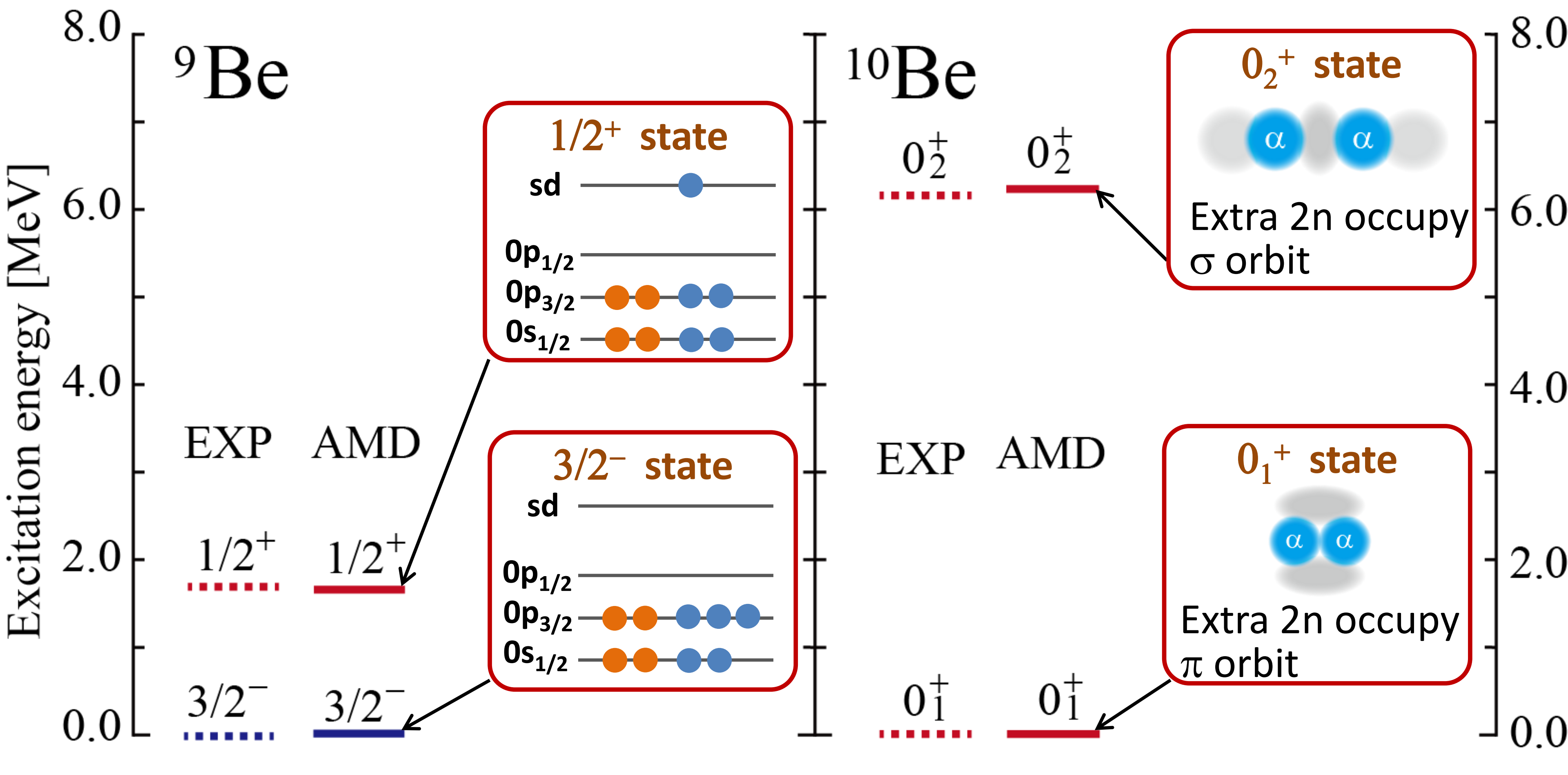
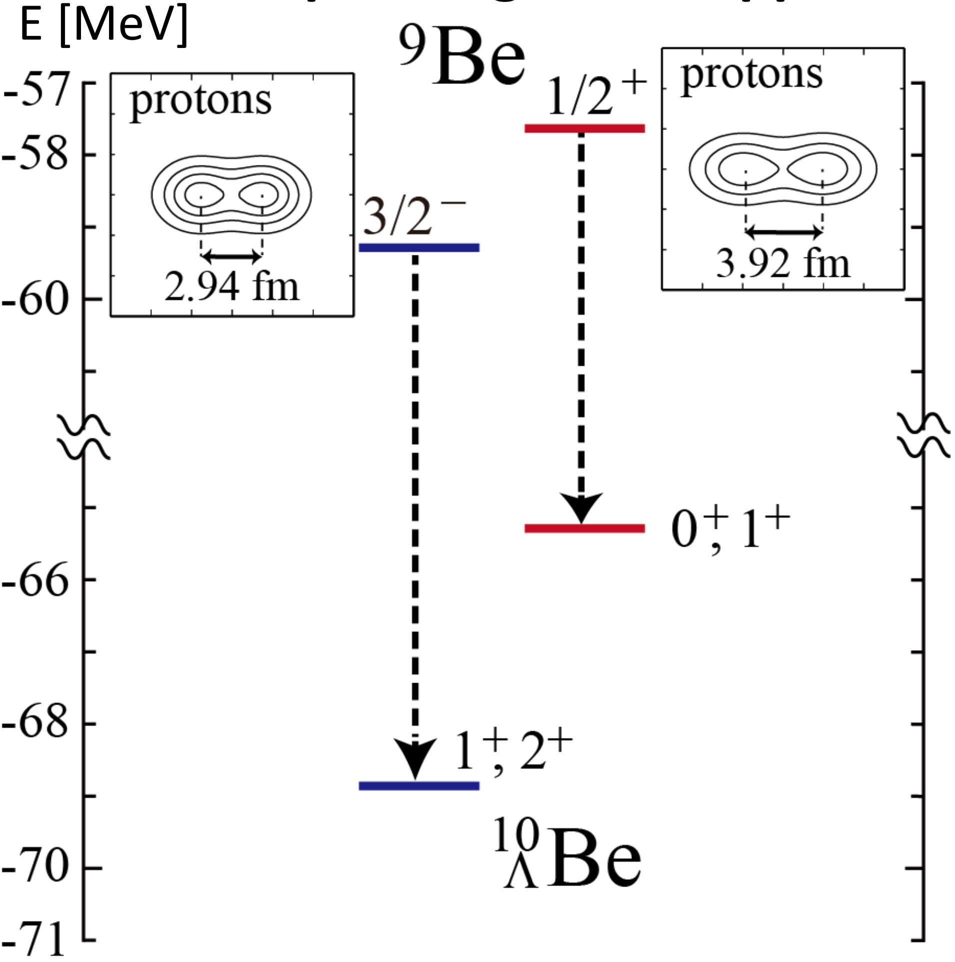
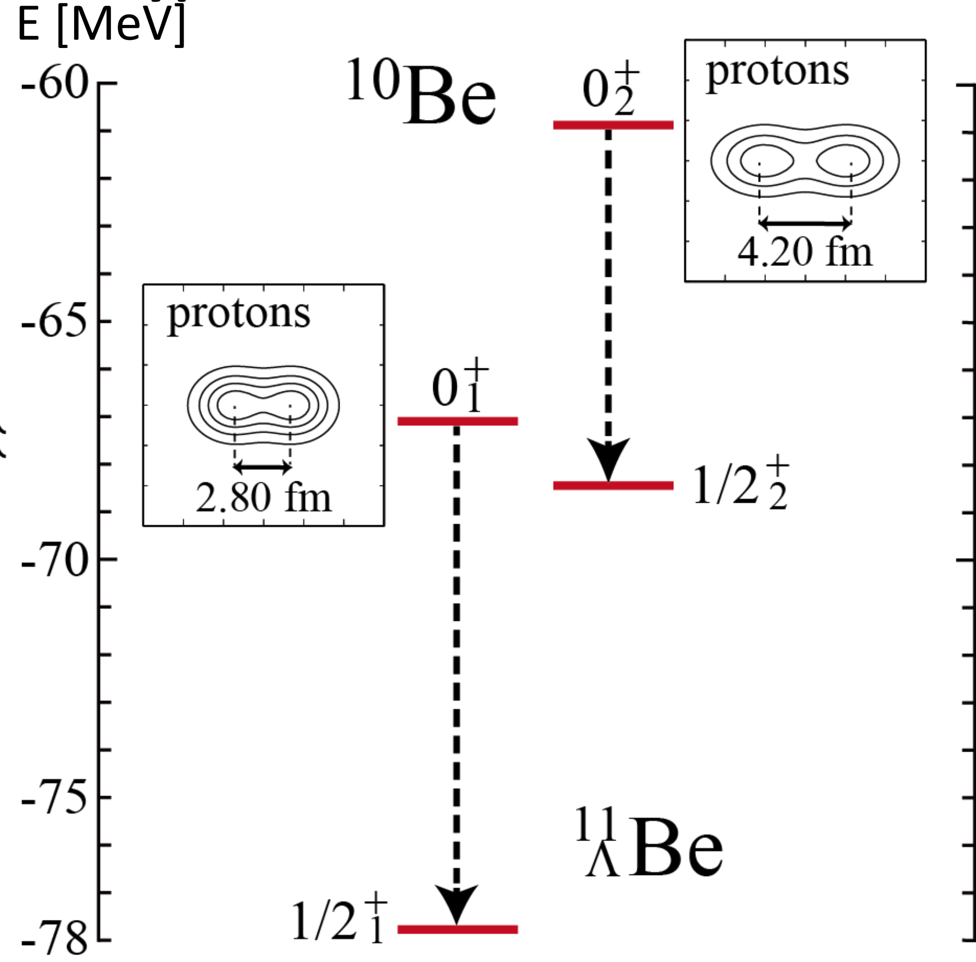


Degrees of 2α clustering is dependent on states

Corresponding states in Be hypernuclei

- **Corresponding states appear in Be hypernuclei**

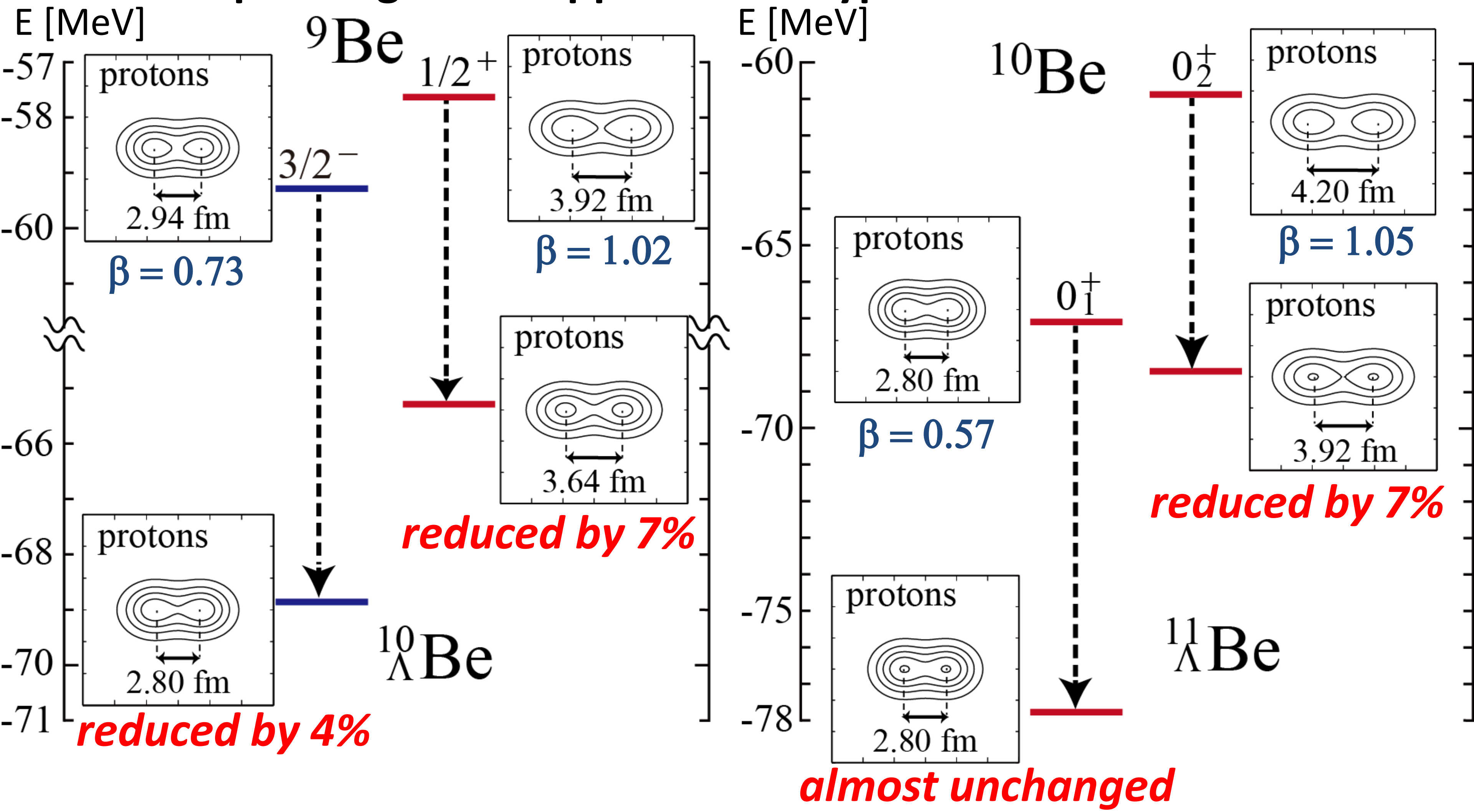




How is structure change?

Change of 2α clustering

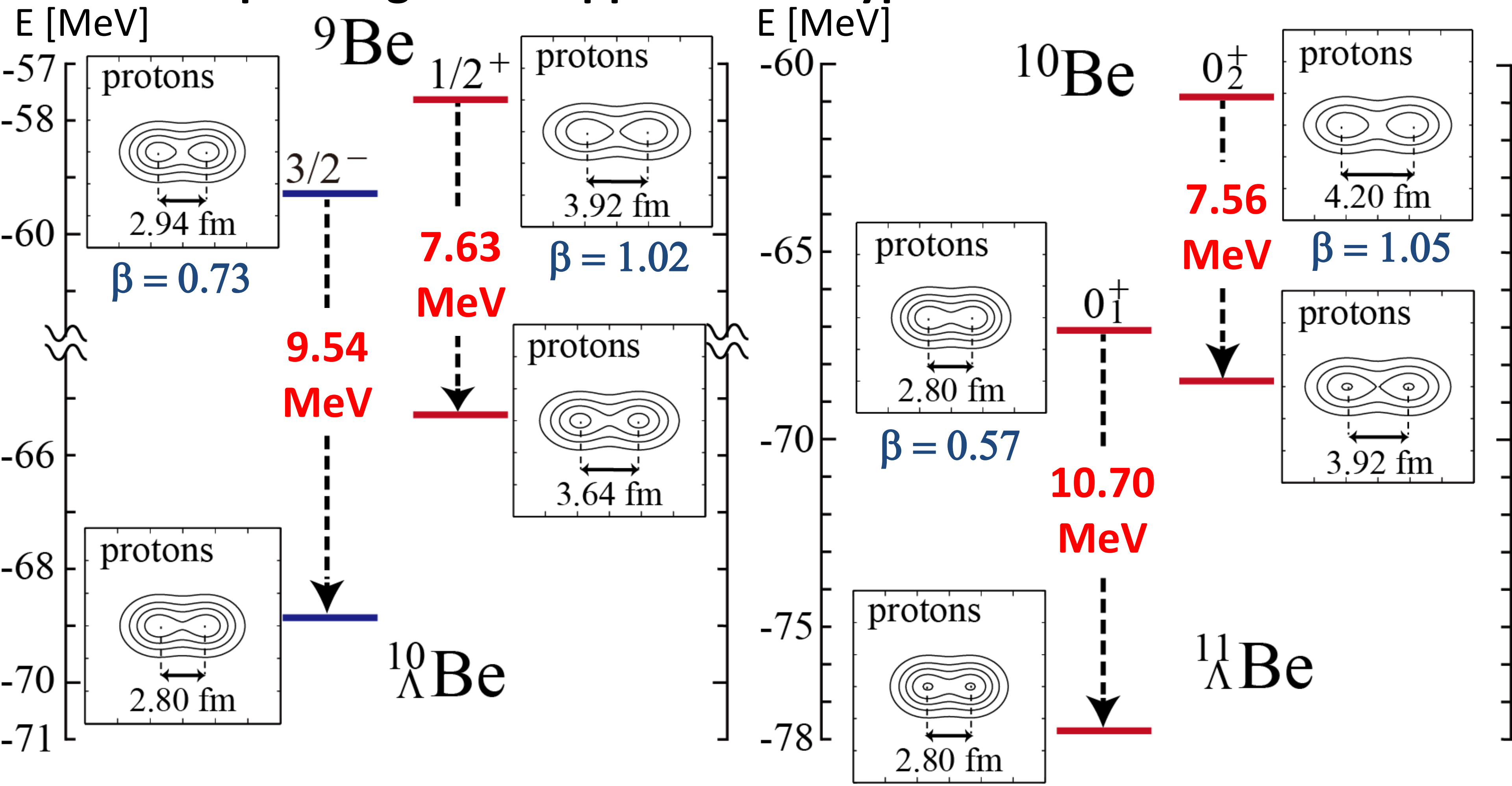
● **Corresponding states appear in Be hypernuclei**



- 2α distance is largely reduced in well developed cluster states
- Difference of 2α clustering still remains despite of large reduction

Difference of B_Λ

- **Corresponding states appear in Be hypernuclei**



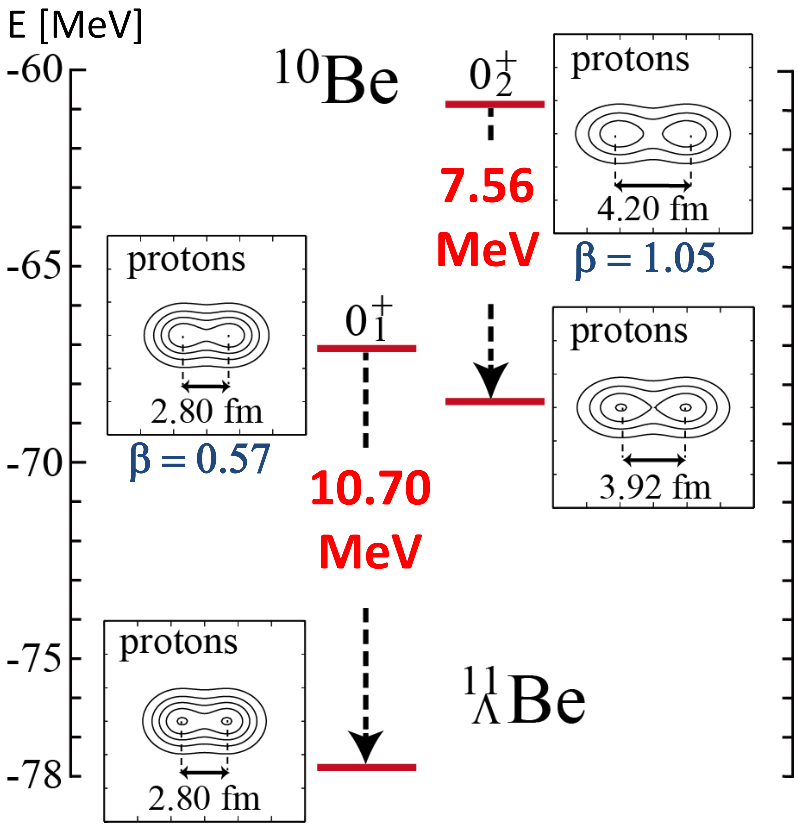
B_Λ : energy gain from the core states

B_Λ (energy gain) is smaller in well-developed cluster states

Difference of B_Λ

◆ Energy components

Ex. $^{11}_{\Lambda}$Be



Energy components

$^{11}_{\Lambda}$Be					^{10}Be	
J^π	E	E_N	T_Λ	$V_{\Lambda N}$	J^π	E
$1/2^+_1$	−77.8	−67.1	7.3	−18.0	0^+_1	−67.2
$1/2^+_2$	−68.4	−60.6	6.4	−14.2	0^+_2	−60.9

E_N: energy of nuclear part in $^{11}_{\Lambda}$Be
T_Λ: kinetic energy of Λ
$V_{\Lambda N}$: ΛN potential energy

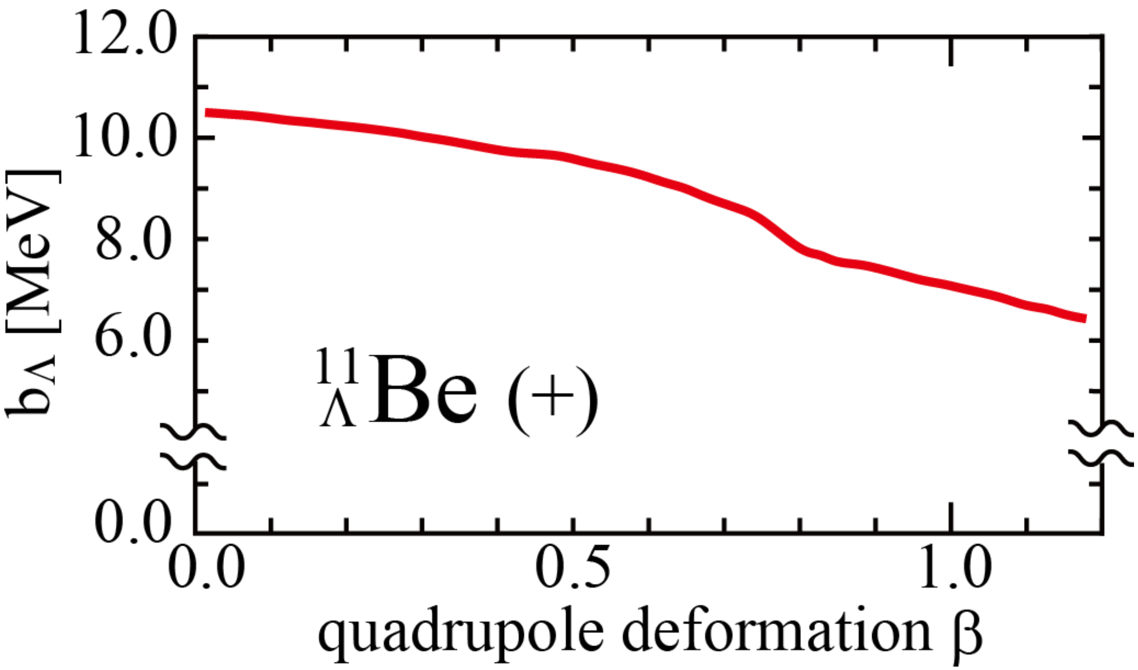
- Main difference of B_Λ comes from that of ΛN potential energy $V_{\Lambda N}$
- Same trend is found in $^{10}_{\Lambda}$Be

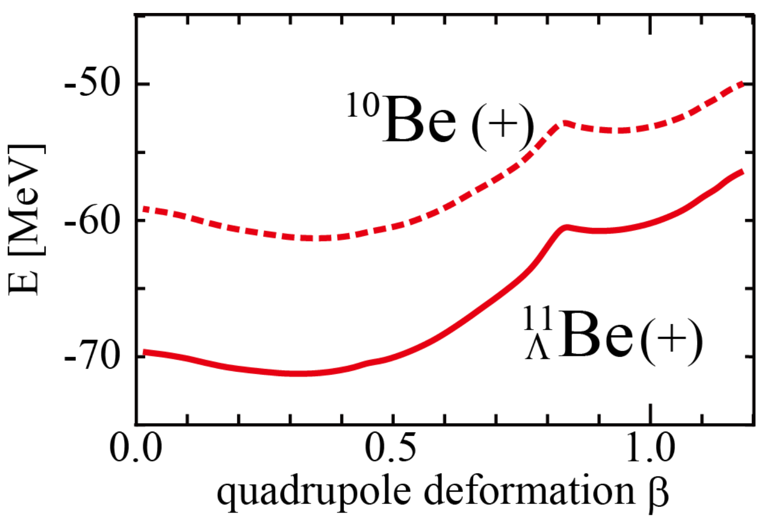
Difference of B_Λ

◆ Λ binding energy and degrees of 2α clustering

Intrinsic energy difference:

$b_\Lambda(\beta) = E_{core}(\beta) - E_{hyp}(\beta)$





Large β corresponds to well-developed 2α clustering

Energy gain b_Λ decreases as β increases mainly due to decreasing overlap

Same trend is found in $^{10}_{\Lambda}$Be

Difference of B_Λ

◆ Λ binding energy and degrees of 2α clustering

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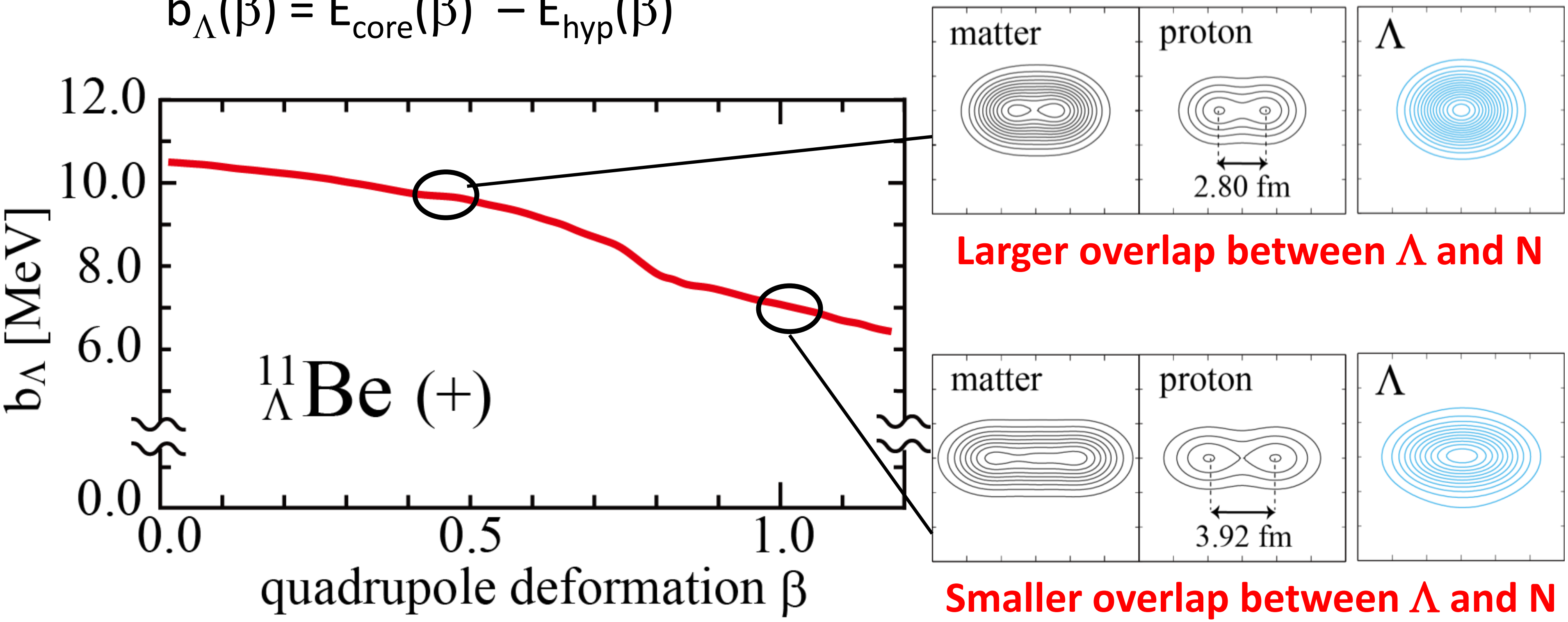
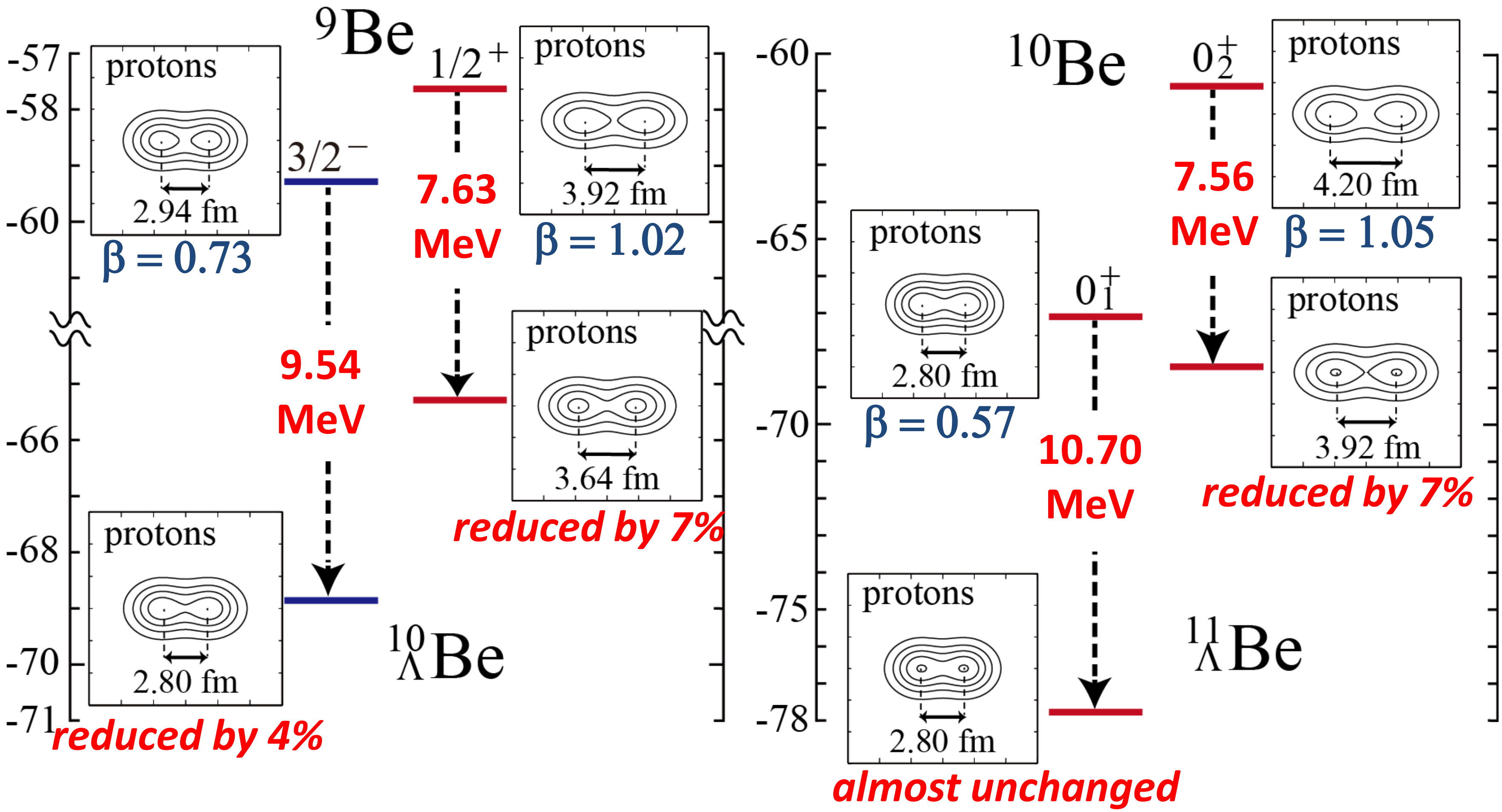


Large β corresponds to well-developed 2α clustering

Energy gain b_Λ decreases as β increases mainly due to decreasing overlap

Same trend is found in $^{10}{}_\Lambda$Be

Structure change in $^{10}{}_{\Lambda}$Be and $^{11}{}_{\Lambda}$Be



- Λ causes dynamical reduction of 2α clustering
- But, the difference of the 2α clustering still remains in hypernuclei

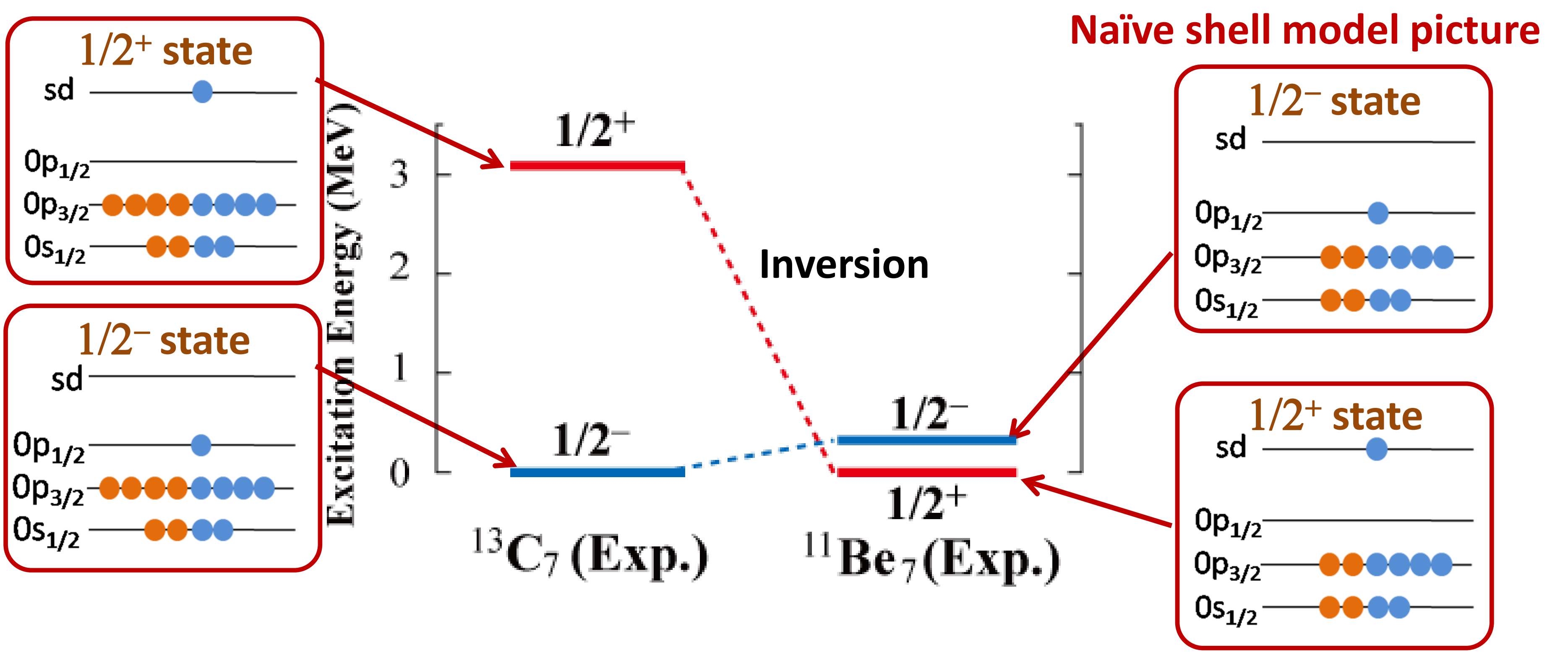
$\longrightarrow$ **Change of excitation spectra due to the difference of B_{Λ}**

Similar phenomena in n-rich hypernucleus $^{12}_{\Lambda}Be$

◆ Parity inverted ground state of n-rich $^{11}_{4}Be_{7}$

- **The ^{11}Be ground state is $1/2^+$, while ordinary nuclei have a $1/2^-$ state as the ground state**

  → **Vanishing of the magic number N=8**



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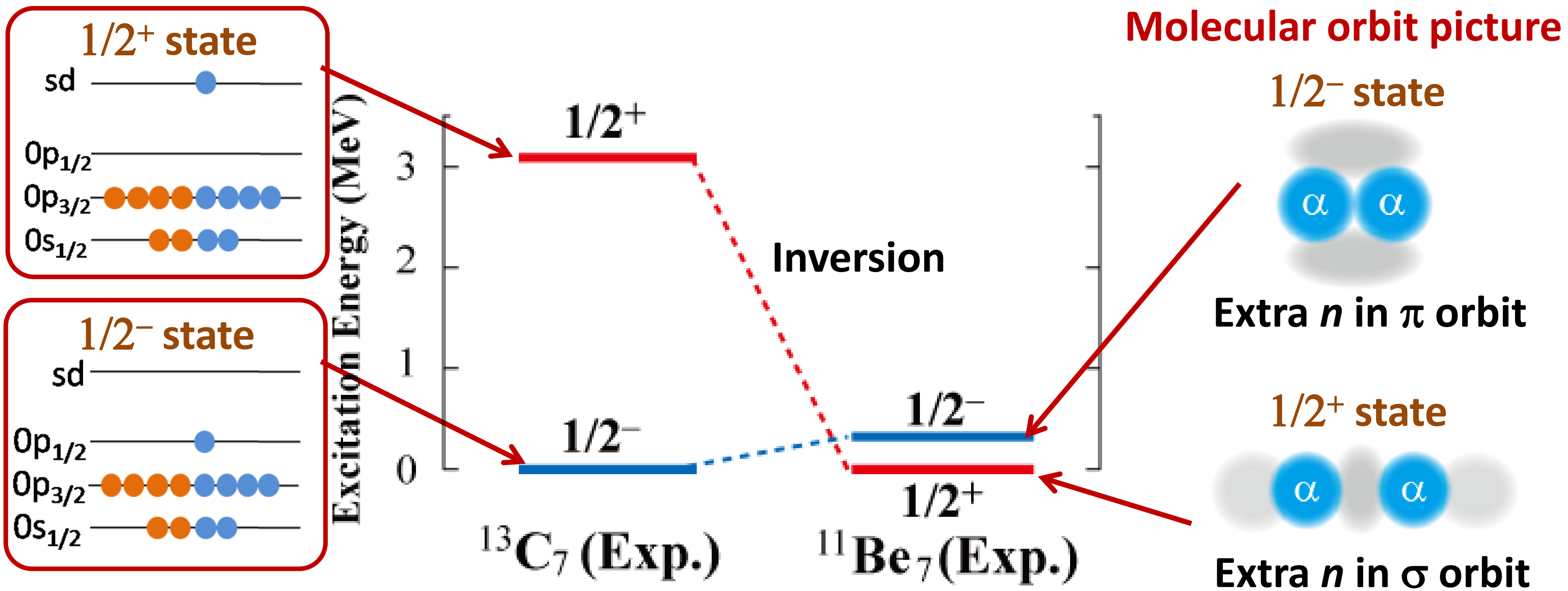

Y. Kanada-En'yo and H. Horiuchi, PRC **66** (2002), 024305.

- 2α clusters with 3 surrounding neutrons occupying molecular orbits (MO)
- MO explains parity inversion, but difficult to see difference of 2α clustering

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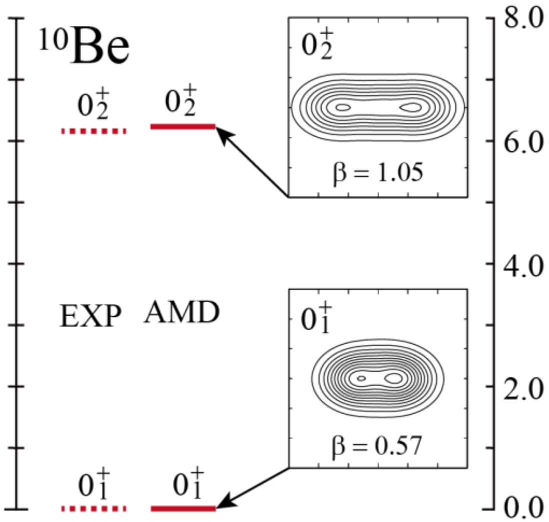
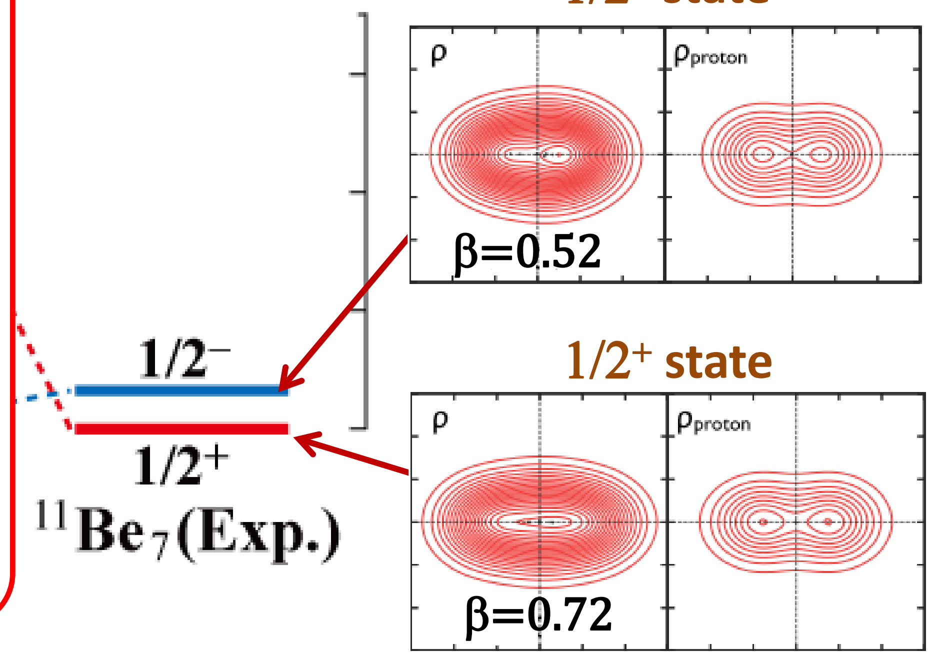
  ⟶ **Vanishing of the magic number N=8**

Similar situation, but degenerated in ^{11}Be



In terms of deformation

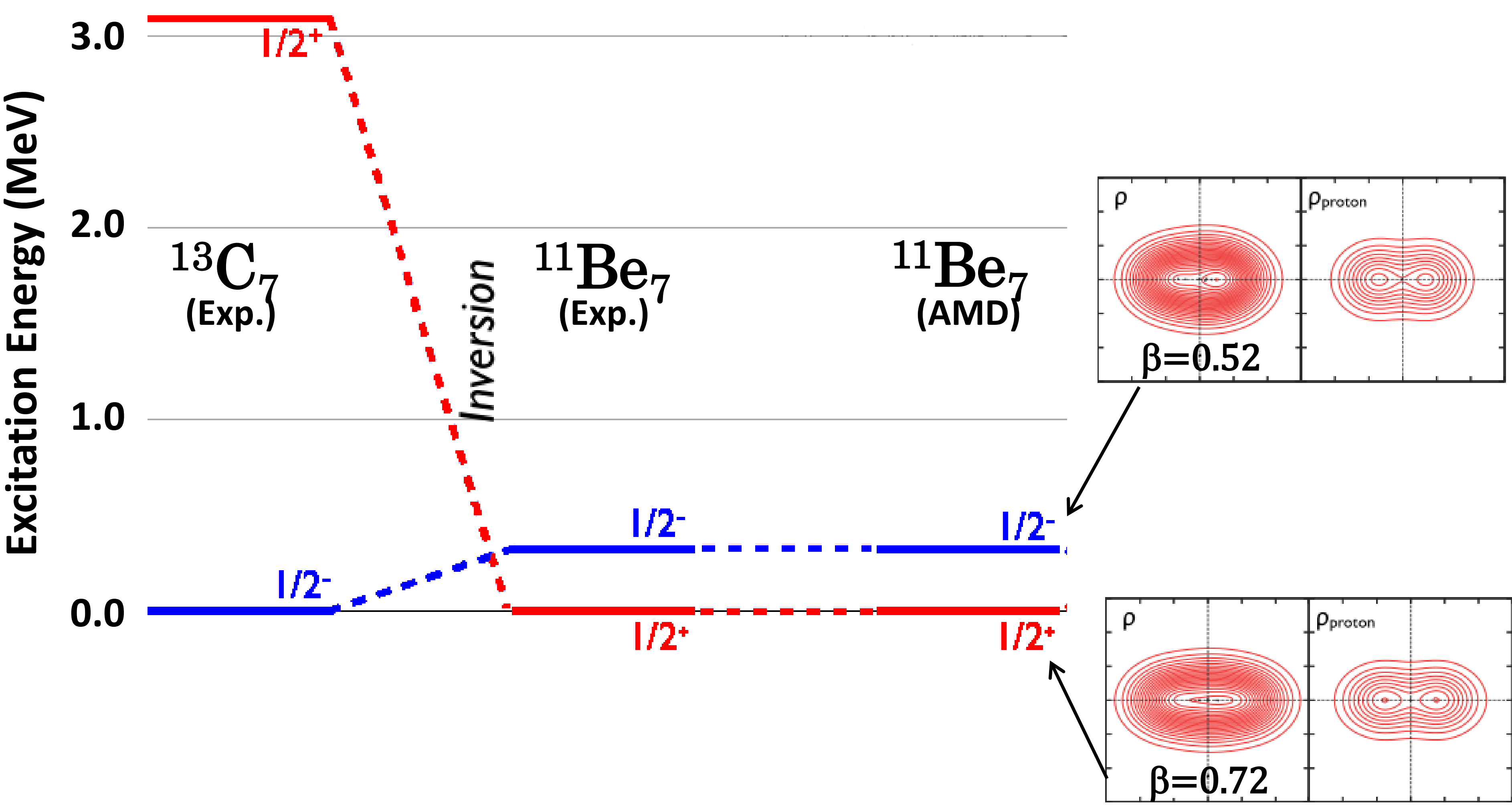
$1/2^-$ state



- 2α clusters with 3 surrounding neutrons occupying molecular orbits (MO)
- MO explains parity inversion, but difficult to see difference of 2α clustering

Results: Parity reversion of $^{12}{}_{\Lambda}$Be

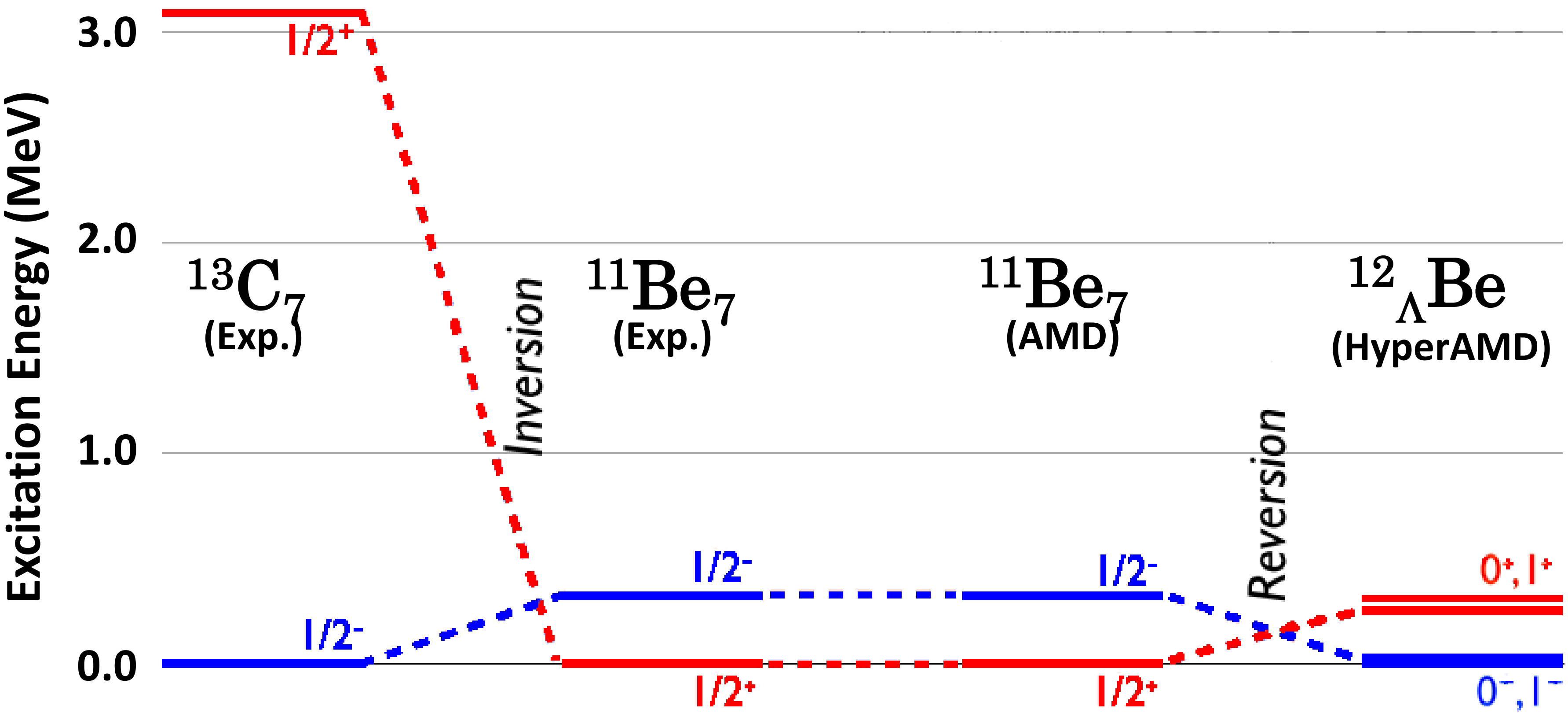
◆ Ground state of $^{12}{}_{\Lambda}$Be



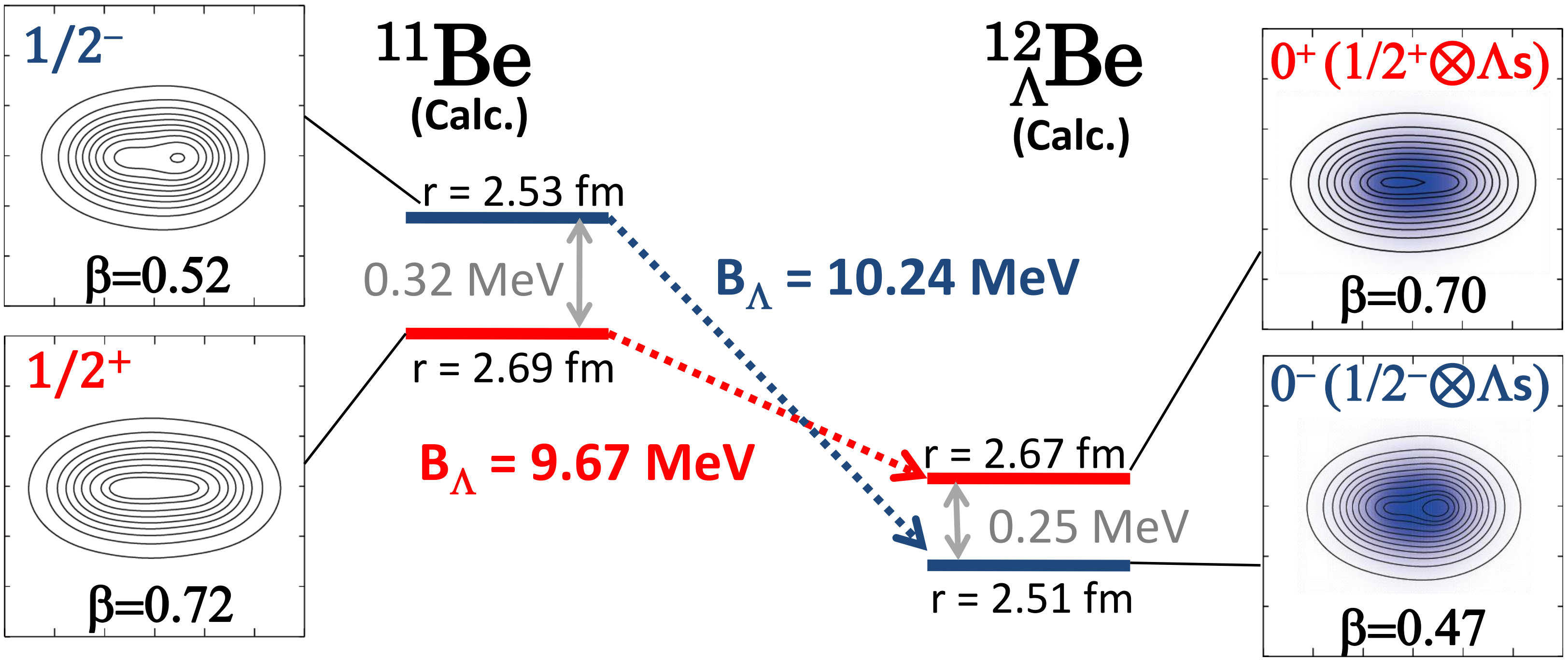
Results: Parity reversion of $^{12}{}_{\Lambda}$Be

◆ Ground state of $^{12}{}_{\Lambda}$Be

- The **parity reversion** of the $^{12}{}_{\Lambda}$Be g.s. occurs by the Λ hyperon



Deformation and Λ binding energy



- **Λ slightly reduces deformations, but the deformation is still different**
- **Λ hyperon coupled to the $1/2^-$ state is more deeply bound than that coupled to the $1/2^+$ state**
  - Due to the difference of the deformation between the $1/2^-$ and $1/2^+$ states

Parity reversion occur reflecting the difference in 2α clustering of ^{11}Be

⟶ could be an evidence for difference of clustering in ^{11}Be

Summary of 1st topic

- **To study structure change by Λ, we applied an extended version of AMD to Be hypernuclei.**

$^{10}{}_{\Lambda}$Be and $^{11}{}_{\Lambda}$Be: changes of various 2α cluster structure

- Λ largely reduces radii of well-developed cluster states
- Difference of deg. of 2α clustering still remains even in Be hypernuclei

$^{12}{}_{\Lambda}$Be: Exotic cluster structure

- The abnormal parity of $^{11}\mathrm{Be}$ ground state is reverted in $^{12}{}_{\Lambda}\mathrm{Be}$

2. Effects of core structure on B_Λ values

Many-body force effects appear in B_Λ?

M.Isaka, Y. Yamamoto and Th.A. Rijken, PRC**94,** 044310(2016)
M. Isaka, Y. Yamamoto and Th.A. Rijken, PRC in print

Individual problems

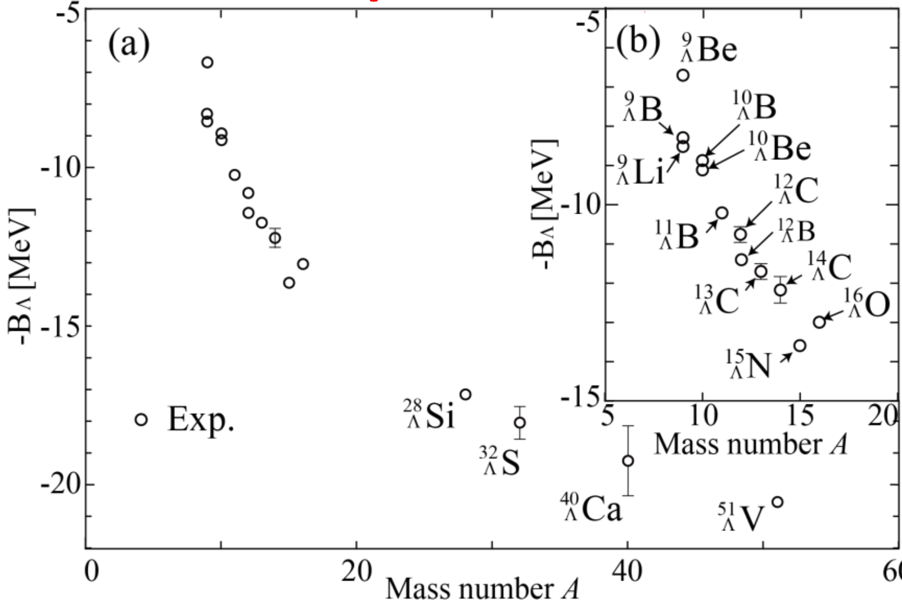
1) B_Λ values and density dependence of the interaction

Today's talk: importance of core description

2) Many-body force effects

Is it possible to describe mass dependence of observed B_Λ?

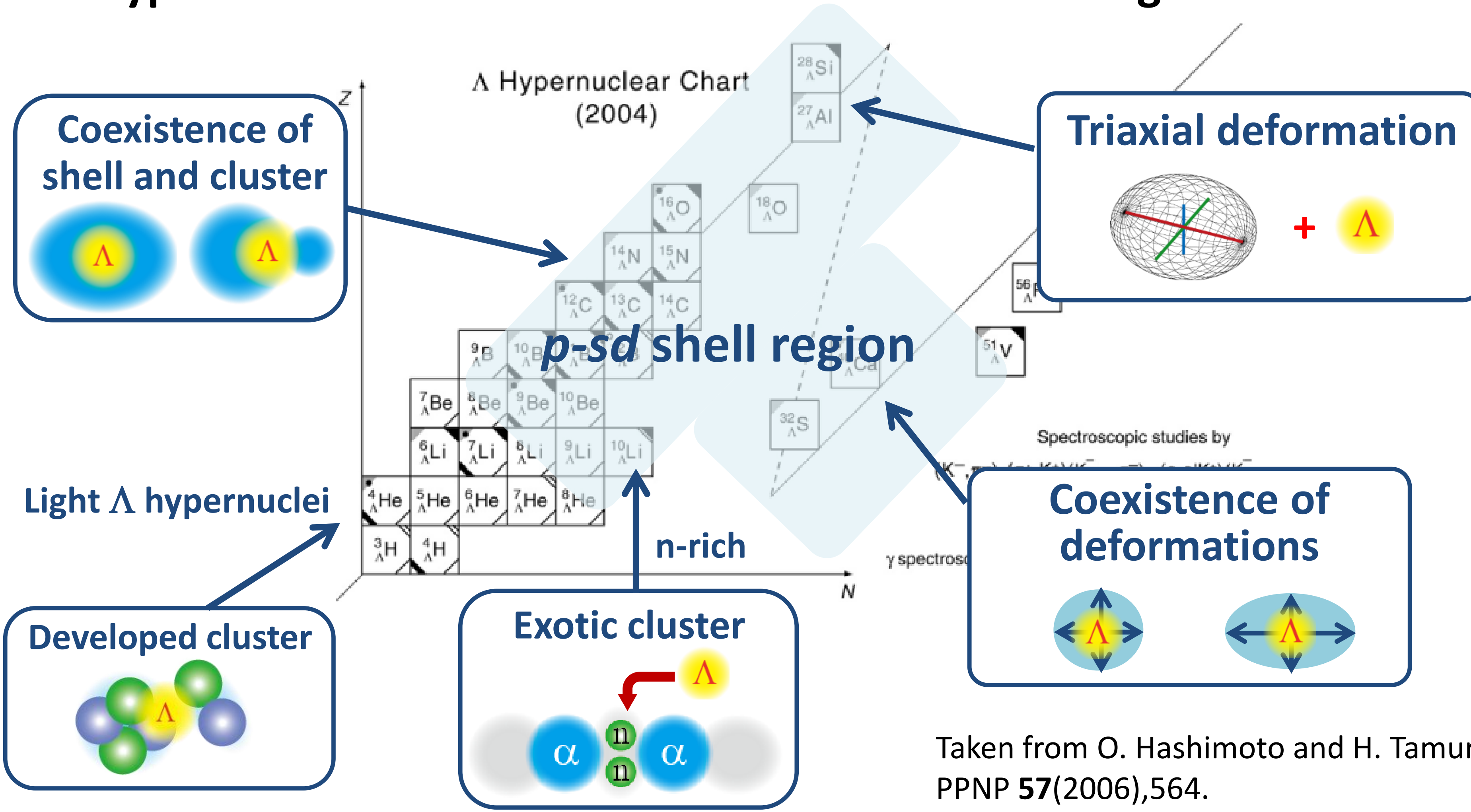
What is essential to reproduce it?



Toward heavier and exotic Λ hypernuclei

Experiments at J-PARC and JLab etc.

- **Hypernuclear chart will be extended to heavier regions**

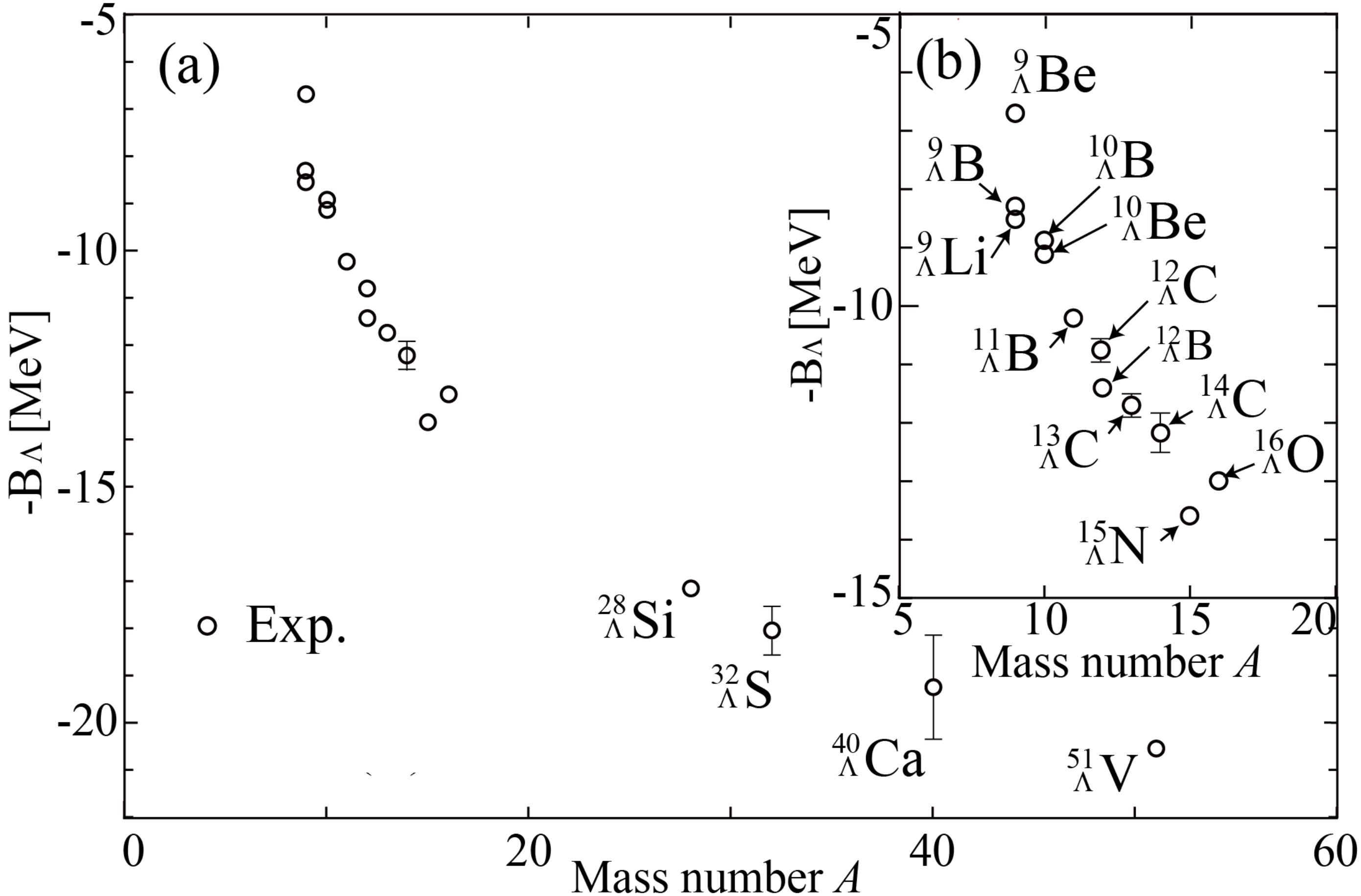


Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Different structure affects B_Λ values through dens. dep. of interaction?

B_Λ as a function of mass number A

Observed data of binding energy of Λ (B_Λ) ($9 \leq A \leq 51$)



"Mass dependence of B_Λ" and "Density dependence of ΛN (ΛNN) interaction"

Bertini *et al*., NPA**83**,306(1979), Davis, Juric , *et al*., NPB**52**(1973), Davis, NPA**547**,369(1992);NPA**754**,3c(2005), Ajimura *et. al*., NPA**639**(1998)93c, Pile *et al*., PRL**66**,2585(1991), Hotchi *et al*., PRC**64**, 044302(2001), Hashimoto and Tamura, PPNP**57**,564(2006), Tang, *et. al*., PRC**90**,034320(2014).

Purpose of this study

◆ Purpose

- **To reveal many-body force effects on B_Λ values based on the interaction model ESC proposed by Nijmegen group**

◆ Individual problems

Today's talk

1) B_Λ and density dependence of the interaction

Is it possible to describe mass dependence of observed B_Λ?

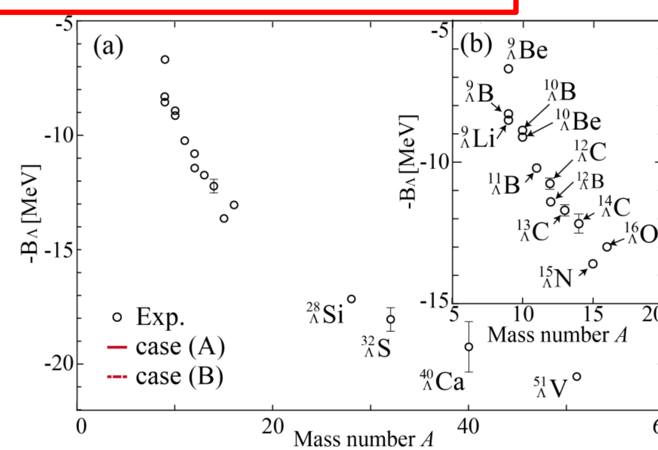
What is essential to reproduce it?

HyperAMD calculation with YNG-ESC08c

M. Isaka, Y. Yamamoto and Th.A. Rijken, PRC**94,** 044310(2016)

2) Many-body force effects

M. Isaka, Y. Yamamoto and Th.A. Rijken, PRC in print



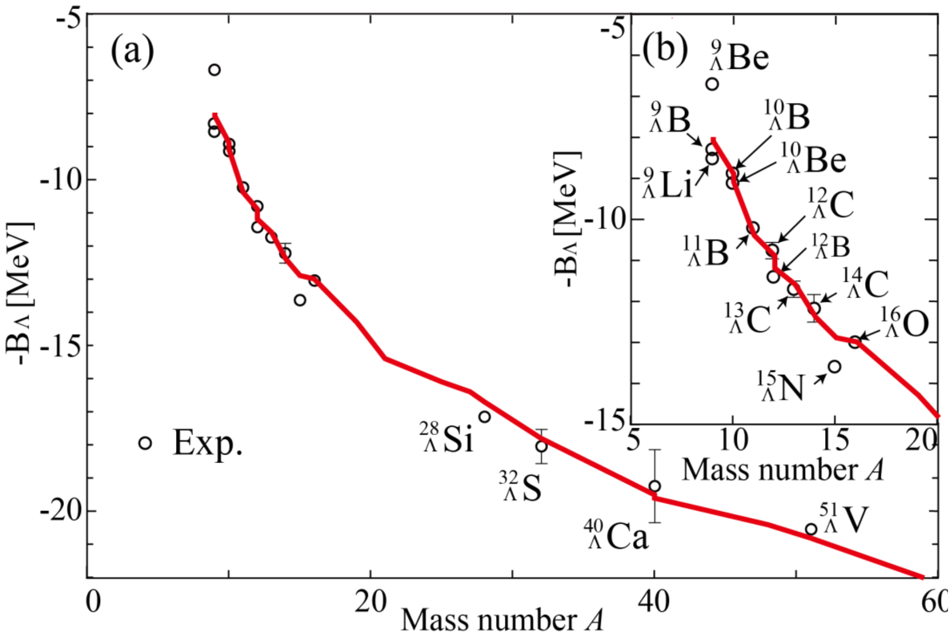
Results: B_Λ as a function of mass number A

HyperAMD w/ ESC08c

$$\langle\rho\rangle = \int dr^3 \rho_N(\mathbf{r})\rho_\Lambda(\mathbf{r})$$

$$k_F = (1+\alpha)\left(\frac{3\pi^2\langle\rho\rangle}{2}\right)^{1/3}$$

Small parameter α is chosen so as to reproduce B_Λ of $^{16}_{\Lambda}$O (α = -0.009)

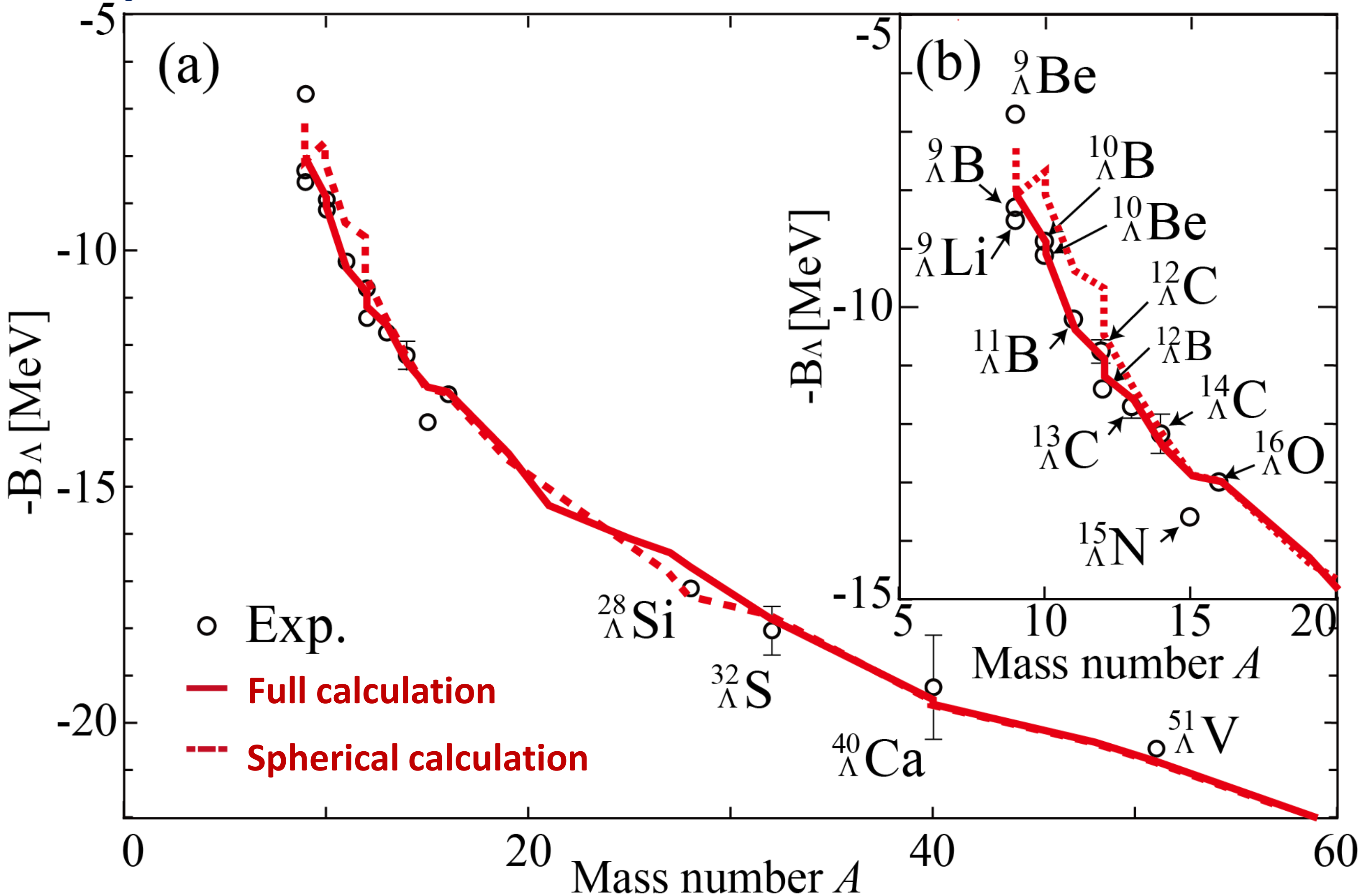


	β	γ	$\langle\rho\rangle$	k_F	$-B_\Lambda^{\mathrm{calc}}$	$-B_\Lambda^{\mathrm{exp}}$
$^{9}_{\Lambda}$Li	0.50	2°	0.072	1.01	−8.1	−8.50 ± 0.12
$^{9}_{\Lambda}$Be	0.87	1°	0.060	0.95	−8.0	−6.71 ± 0.04
$^{9}_{\Lambda}$B	0.45	2°	0.072	1.01	−8.1	−8.29 ± 0.18
$^{10}_{\Lambda}$Be	0.57	1°	0.077	1.04	−8.9	−9.11 ± 0.22
						−8.55 ± 0.18
$^{10}_{\Lambda}$B	0.58	1°	0.075	1.03	−9.1	−8.89 ± 0.12
$^{11}_{\Lambda}$B	0.50	29°	0.081	1.05	−10.4	−10.24 ± 0.05
$^{12}_{\Lambda}$B	0.39	48°	0.083	1.06	−11.2	−11.37 ± 0.06
						−11.38 ± 0.02
$^{12}_{\Lambda}$C	0.41	34°	0.086	1.07	−10.9	−10.76 ± 0.19
$^{13}_{\Lambda}$C	0.45	60°	0.090	1.09	−11.6	−11.69 ± 0.19
$^{14}_{\Lambda}$C	0.45	31°	0.093	1.10	−12.4	−12.17 ± 0.33
$^{15}_{\Lambda}$N	0.28	60°	0.098	1.12	−12.9	−13.59 ± 0.15
$^{16}_{\Lambda}$O	0.02	–	0.105	1.15	−13.0	−12.96 ± 0.05
$^{19}_{\Lambda}$O	0.30	3°	0.110	1.17	−14.3	–
$^{21}_{\Lambda}$Ne	0.46	0°	0.106	1.15	−15.4	–
$^{25}_{\Lambda}$Mg	0.478	21°	0.116	1.19	−16.1	–
$^{27}_{\Lambda}$Mg	0.36	36°	0.125	1.22	−16.4	–
$^{28}_{\Lambda}$Si	0.32	53°	0.125	1.22	−16.7	−17.1 ± 0.02
$^{32}_{\Lambda}$S	0.28	0°	0.130	1.23	−17.8	−18.0 ± 0.5
$^{40}_{\Lambda}$K	0.01	–	0.136	1.25	−19.6	–
$^{40}_{\Lambda}$Ca	0.03	–	0.136	1.25	−19.5	−19.24 ± 1.1
$^{41}_{\Lambda}$Ca	0.13	12°	0.136	1.25	−19.7	–
$^{48}_{\Lambda}$K	0.01	–	0.141	1.27	−20.4	–
$^{51}_{\Lambda}$V	0.18	2°	0.151	1.30	−20.8	−20.51 ± 0.13
$^{59}_{\Lambda}$Fe	0.26	23°	0.142	1.27	−22.0	–

HyperAMD w/ ESC08c successfully reproduces B_Λ in wide mass regions

What is essential to reproduce B_Λ?

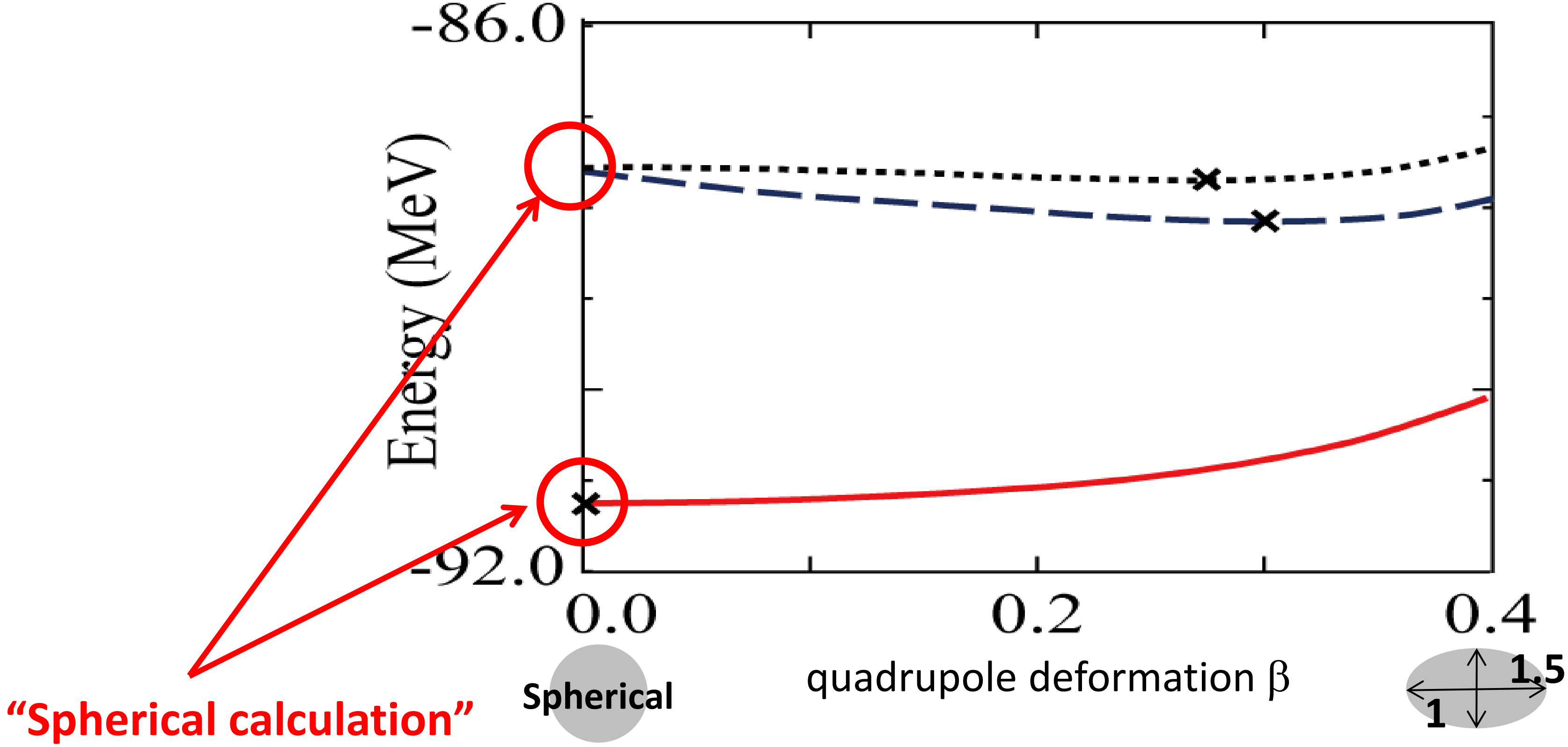
◆ Description of the core nuclei



What is essential to reproduce B_Λ?

◆ Description of the core nuclei

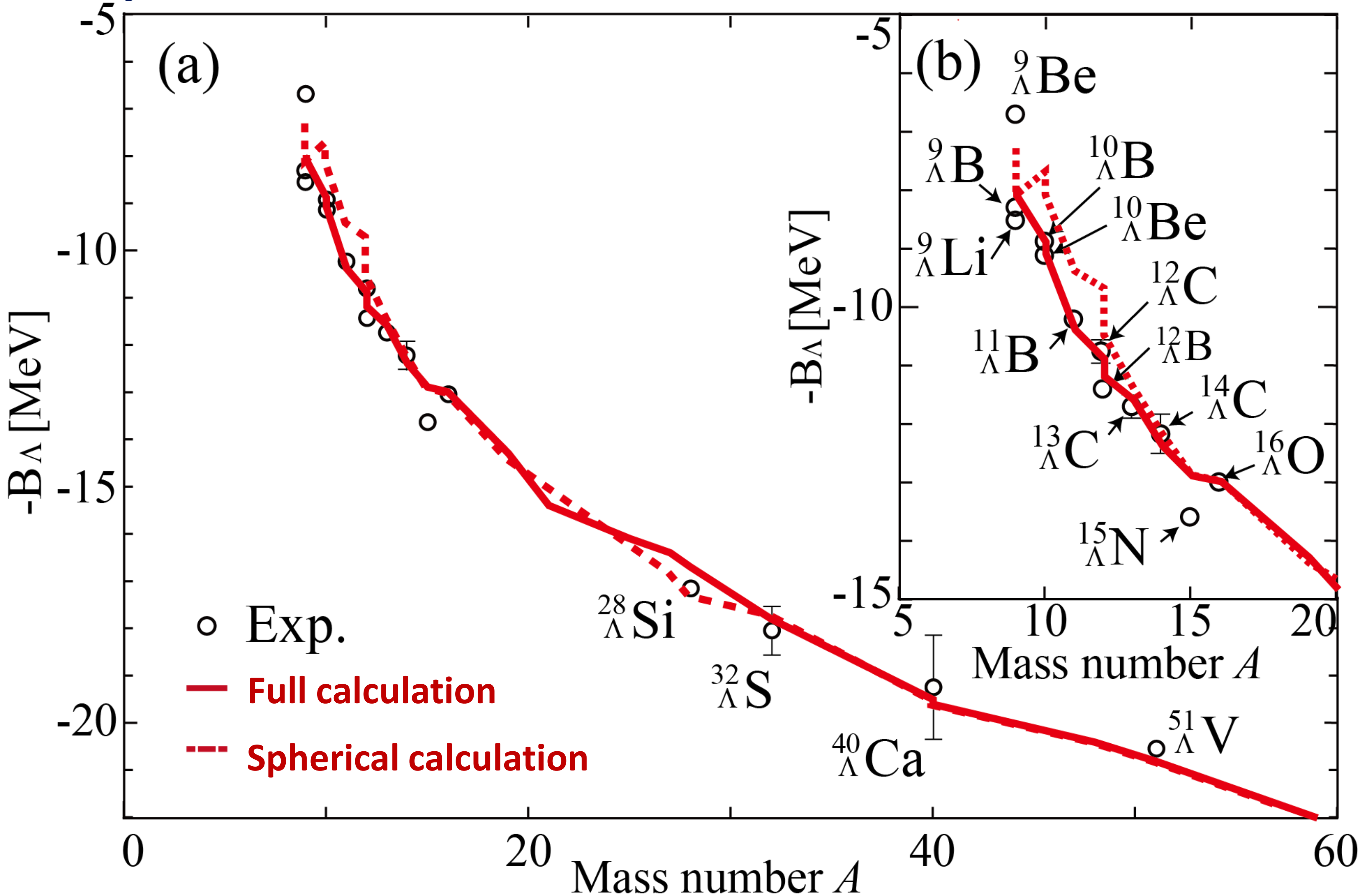
- **"Full calculation" vs. "Spherical calculation"**



"Full calculation": all of the intrinsic w.f. are used in the GCM calc.

What is essential to reproduce B_Λ?

◆ **Description of the core nuclei**



Deformation of the ground states is essential to reproduce B_Λ

What is essential to reproduce B_Λ?

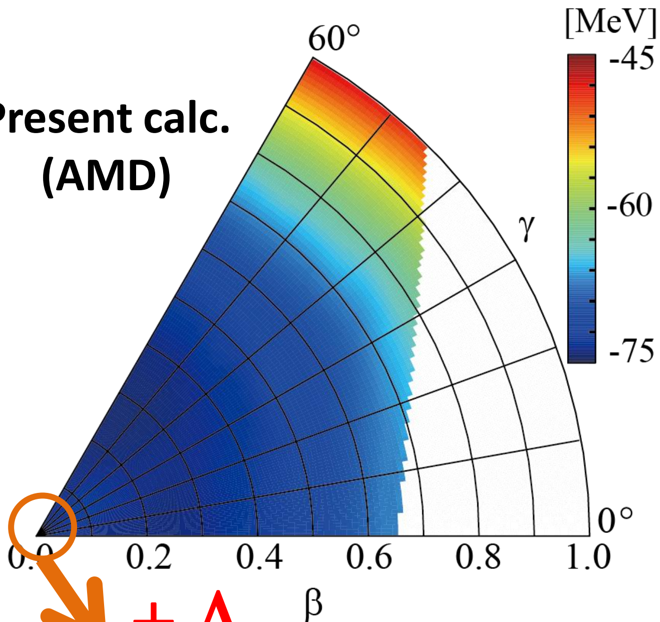
"Description of the core structure"

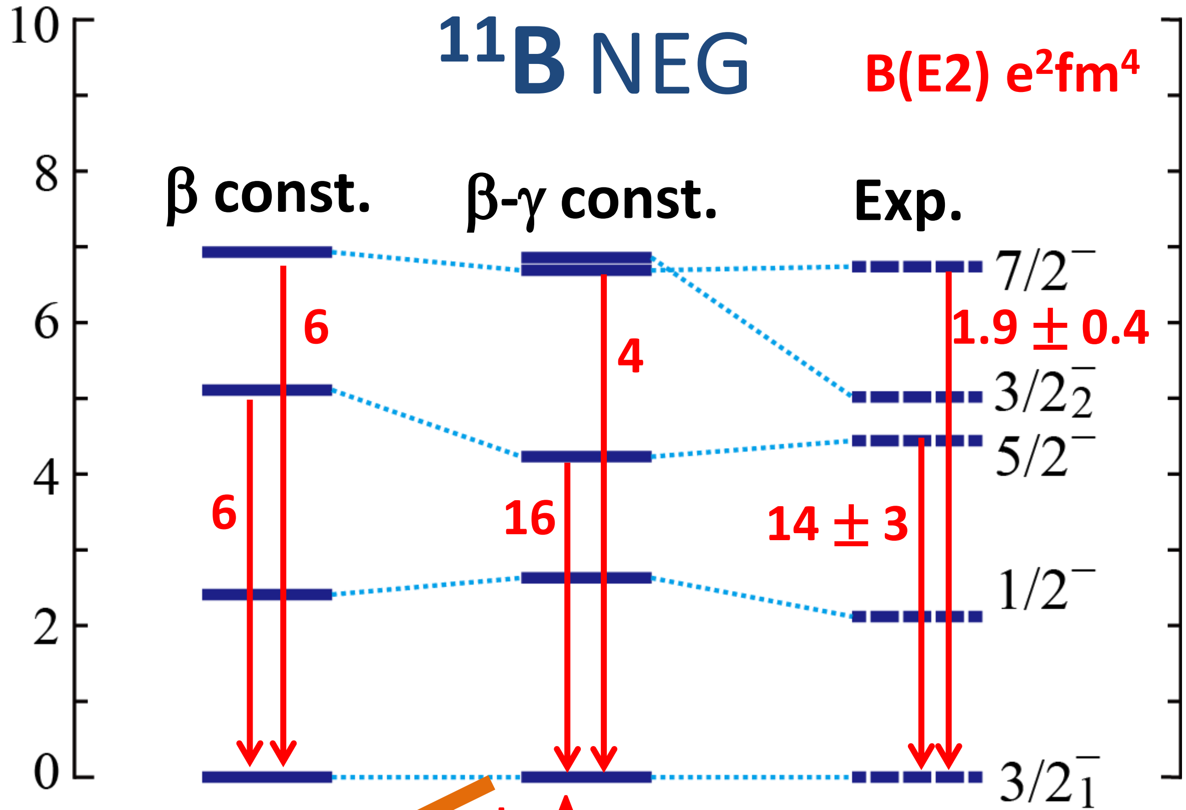
Ex.: ^{11}B

More sophisticated treatment: GCM calc. on (β, γ) plane

T. Suhara and Y. Kanada-En'yo, PTP**123**,303(2010)

Present calc. (AMD)





+ Λ

+ Λ

$^{12}{}_\Lambda$B (Spherical)

B_Λ = 9.7 MeV

(k_F = 1.15 fm^{-1})

$^{12}{}_\Lambda$B (β-γ)

B_Λ = 11.2 MeV

(k_F = 1.06 fm^{-1})

$^{12}{}_\Lambda$B (EXP)

B_Λ = 11.4 ±0.02 MeV

Summary and future plans

◆ Summary

- **To study structure change by Λ in cluster states of Be hypernuclei**
  - **$^{10}{}_{\Lambda}$Be and $^{11}{}_{\Lambda}$Be: changes of various 2α cluster structure**
    - Λ largely reduces radii of well-developed cluster states
    - Difference of deg. of 2α clustering still remains even in Be hypernuclei
  - **$^{12}{}_{\Lambda}$Be: Exotic cluster structure**
    - The abnormal parity of $^{11}\mathrm{Be}$ ground state is reverted in $^{12}{}_{\Lambda}\mathrm{Be}$
- **Systematics of B_{Λ} and density dependence of the ΛN interaction**
  - Proper description of the core nuclei is important for B_{Λ} values

◆ Future plans

- **Structure study of hypernuclei**
  - α clustering of both single and double Λ hypernuclei
- **Based on structure calculation**
  - CSB effects in medium-heavy hypernuclei