ハイパー核の不純物効果と
ハイペロン·プローブで探る原子核構造研究

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Hypernucleus

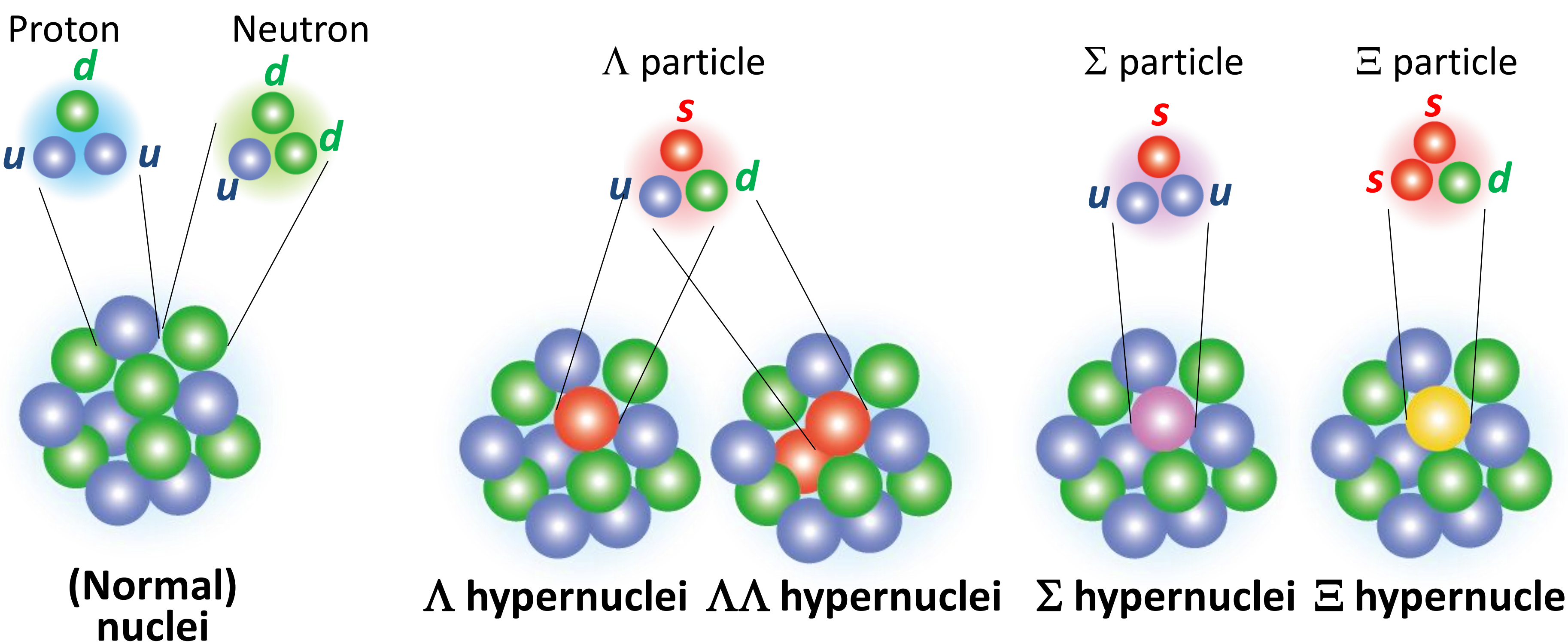
◆ **Normal nuclei**

- **Nucleons**
  - **proton**
  - **neutron**

◆ **Hypernuclei**

- **Nucleons and hyperon(s) (Λ, Σ, Ξ)**
- **Hyperons have strange quark(s)**

→ **Hypernuclei are nuclei with *s* quark(s)**



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

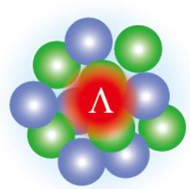
Structure: To understand many-body system of nucleons and hyperon

- **Addition of hyperon(s) shows us new aspects of nuclear structure**

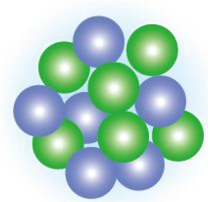
Ex.) Structure change by hyperon(s)

- No Pauli exclusion between N and Y
- YN interaction is different from NN

"Hyperon as an impurity in nuclei"



Λ hypernucleus



Normal nucleus

+

As an impurity

"Structure of (Λ) hypernuclei"

Unique aspects of Λ hypernuclei

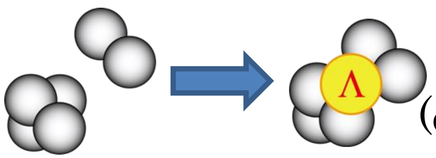
- Λ has **no Pauli blocking** to nucleons
- ΛN **attraction** (different from NN)

Unique phenomena

Structure change:

Shrinkage of the inter-cluster distance

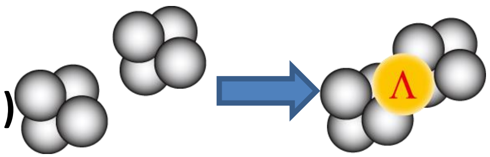
^{6}Li (α + d)



$^{7}_{\Lambda}$Li (α + d + Λ)

"Glue-like role" of Λ

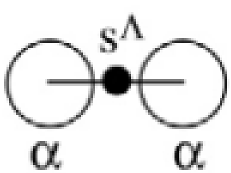
^{8}Be **(unbound)**



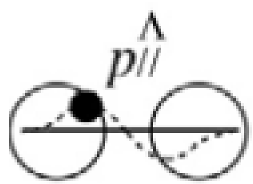
$^{9}_{\Lambda}$Be **(bound)**

Genuine hypernuclear (super symmetric) states:

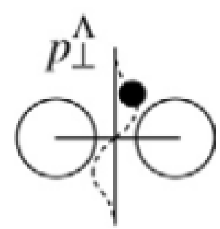
$^{9}_{\Lambda}$Be



ground state



Genuine hypernuclear state
(Super-symmetric state)



^{9}Be analog

A unique probe: Λ can penetrate into nuclear interior

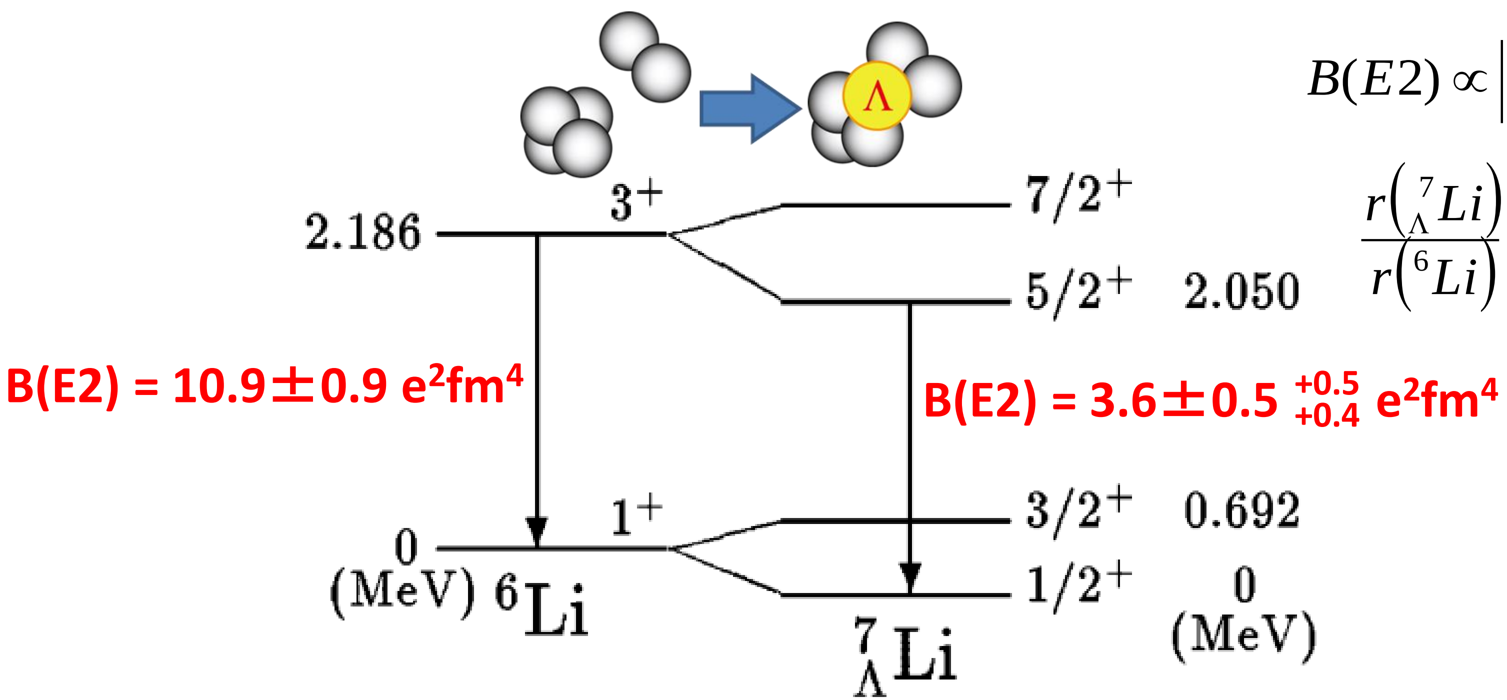
Structure change by Λ: "Shrinkage effect"

Shrinkage effect: Λ makes nucleus compact

Example: $^{7}_{\Lambda}\mathrm{Li}$ [1,2]

T. Motoba, et al., PTP **70**, 189 (1983); T. Motoba, et al., PTPS **81**, 42(1985).
E. Hiyama, et al., Phys. Rev. C**59** (1999), 2351.
K. Tanida, et al., Phys. Rev. Lett. **86** (2001), 1982.

- **$^{6}\mathrm{Li}$: α + d cluster structure**
- **Λ hyperon penetrates into the nuclear interior**
- **Λ hyperon reduces α + d distance** → **B(E2) reduction (Observable)**



$$B(E2) \propto \left| \left\langle \Psi_f \left| r^2 Y_{2\mu}(\hat{r}) \right| \Psi_i \right\rangle \right|^2$$

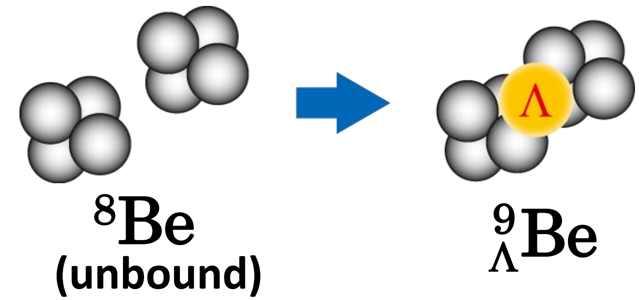
$$\frac{r\left(^{7}_{\Lambda}Li\right)}{r\left(^{6}Li\right)} \approx \left(\frac{B(E2;{}^{7}_{\Lambda}Li)}{B(E2;{}^{6}Li)} \right)^{1/4}$$

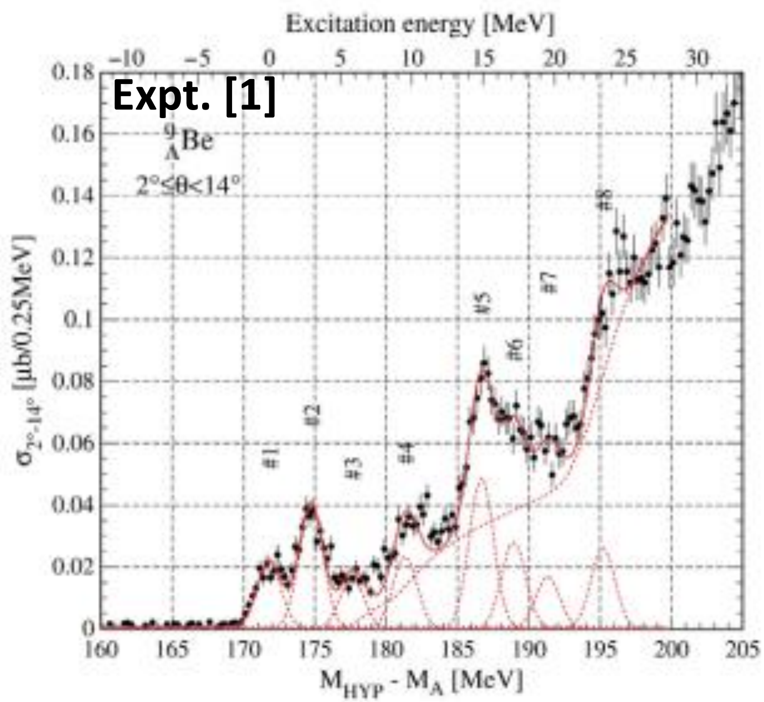
Structure change by Λ: "Glue-like role"

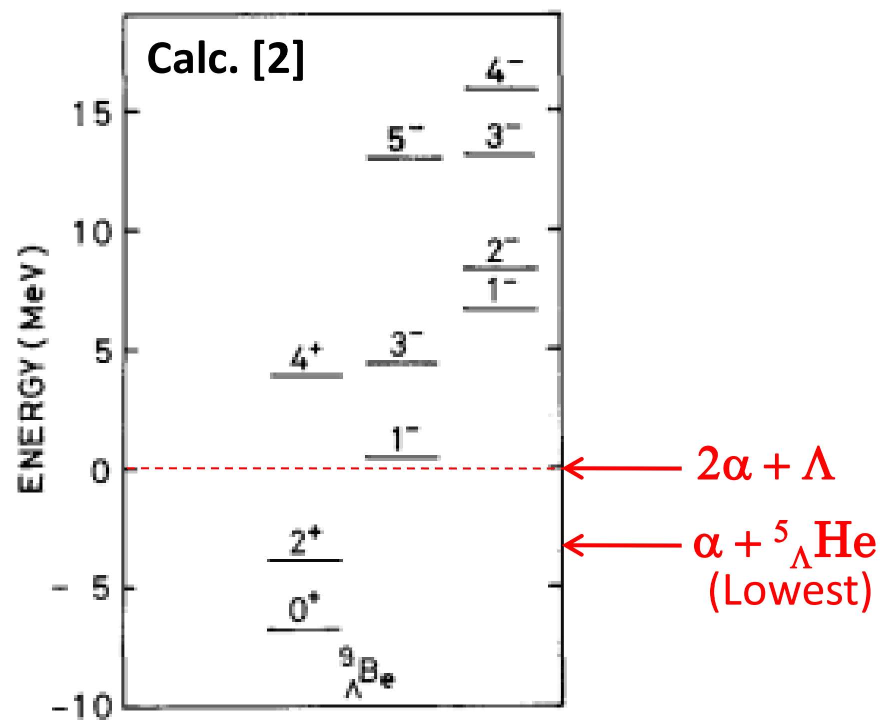
Glue-like role: Λ hyperon stabilizes unbound state

Example: ${}^{9}_{\Lambda}\mathrm{Be}$

- **^{8}Be is an unstable nucleus**
  - **Its g.s. lies at about 100 keV above $\alpha + \alpha$ threshold**
- **${}^{9}_{\Lambda}$Be is bound with an $\alpha + \alpha + \Lambda$ structure**







[1] O. Hashimoto, et. al., NPA **639** (1998) 93c. [2] H. Bando, et. al., PTP **69** (1982) 913.

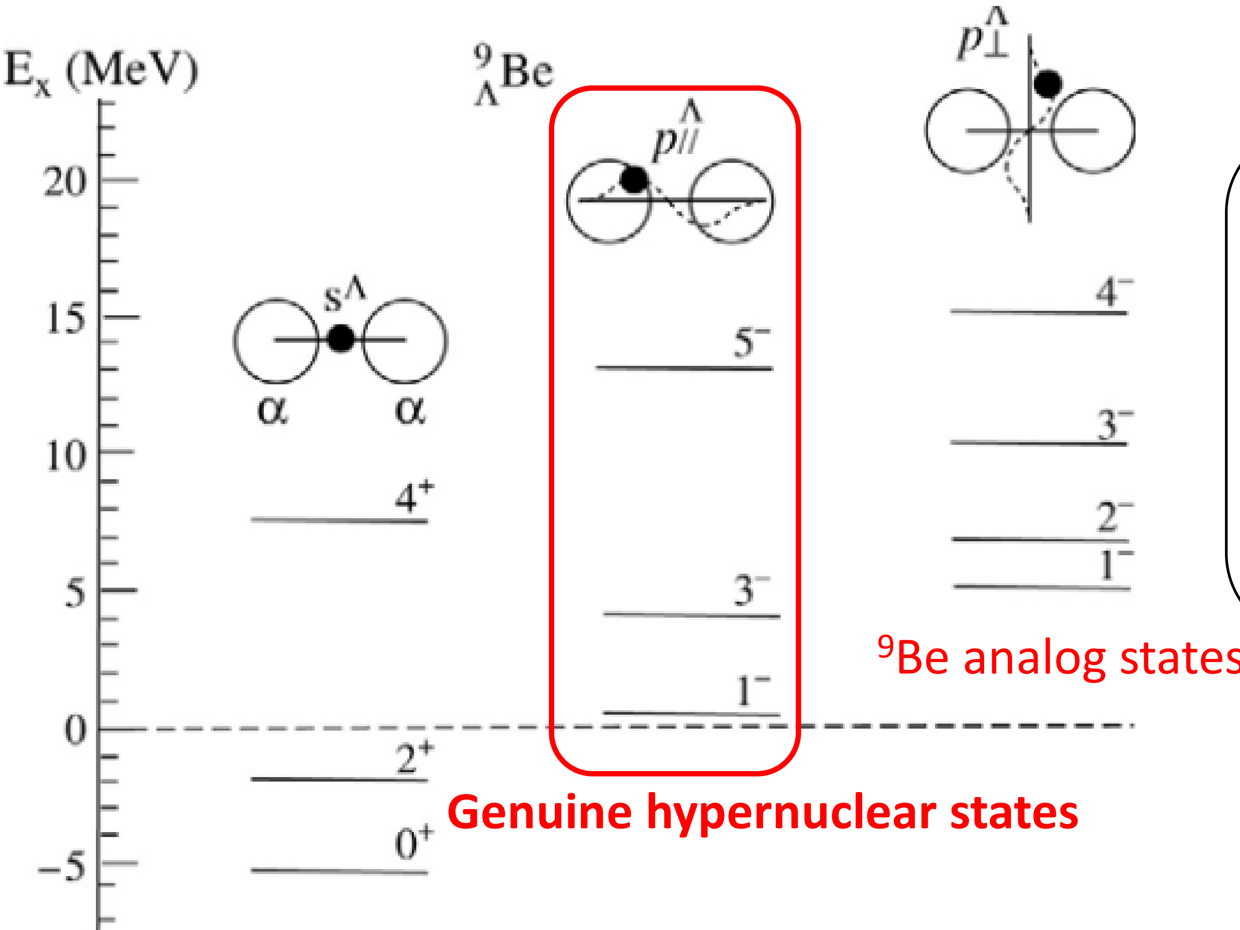
Genuine hypernuclear (super symmetric) state

Genuine hypernuclear states cannot be formed in ordinary ^{9}Be

Example: $^{9}_{\Lambda}$Be

- **$^{9}{}_{\Lambda}$Be: $\alpha + \alpha + \Lambda$ structure**

R.H. Dalitz, A. Gal, PRL **36** (1976) 362.
H. Bando, et al., PTP **66** (1981) 2118.;
H. Bando, Nuclear Phys. A **450** (1986) 217c



In case of ^{9}Be ($\alpha + \alpha$ + n)

Forbidden by Pauli principle

allowed

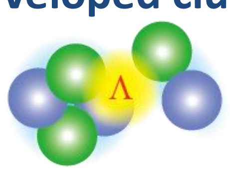
Observed Λ hypernuclei

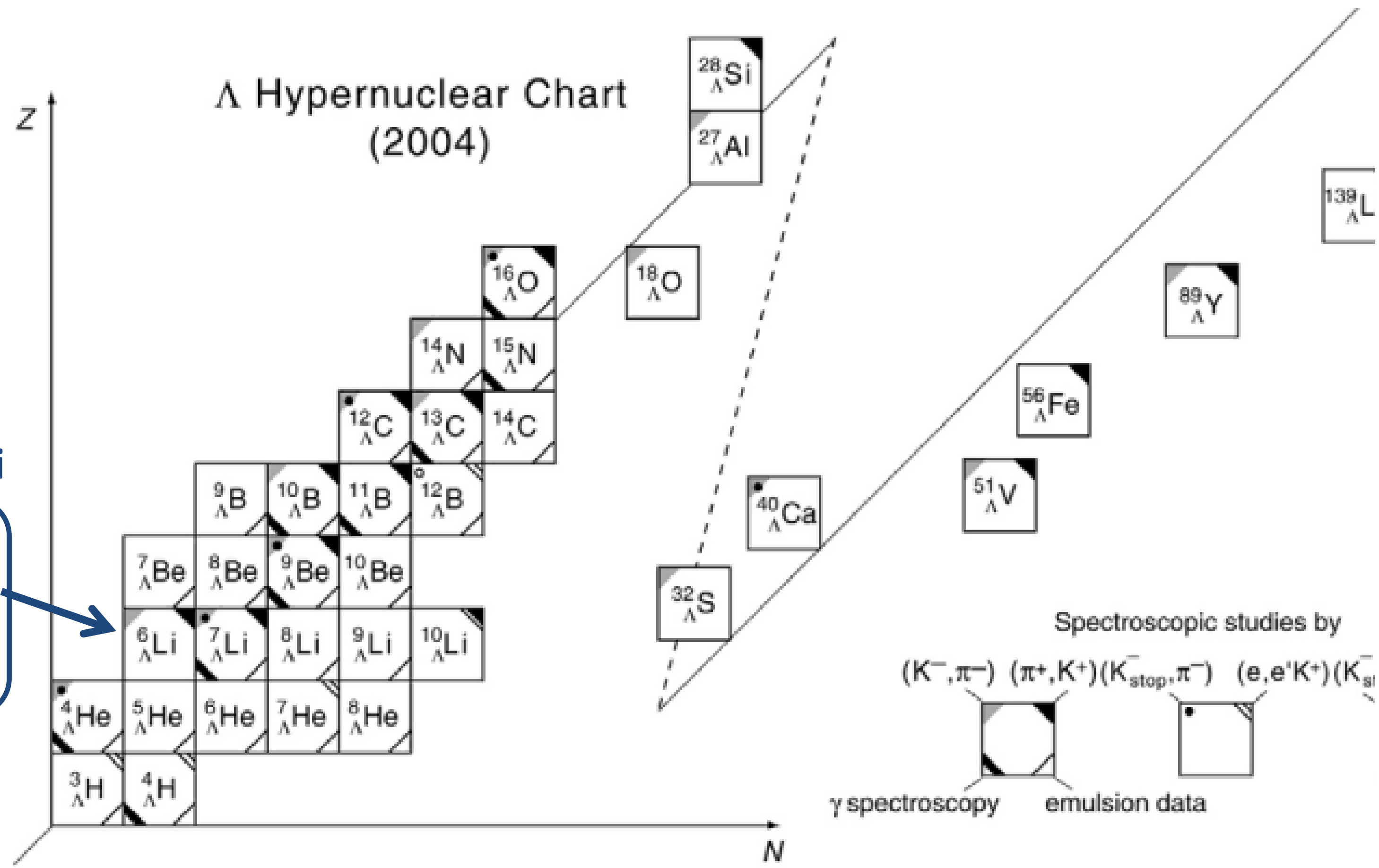
Λ hypernuclei observed so far

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

Light Λ hypernuclei

Developed cluster





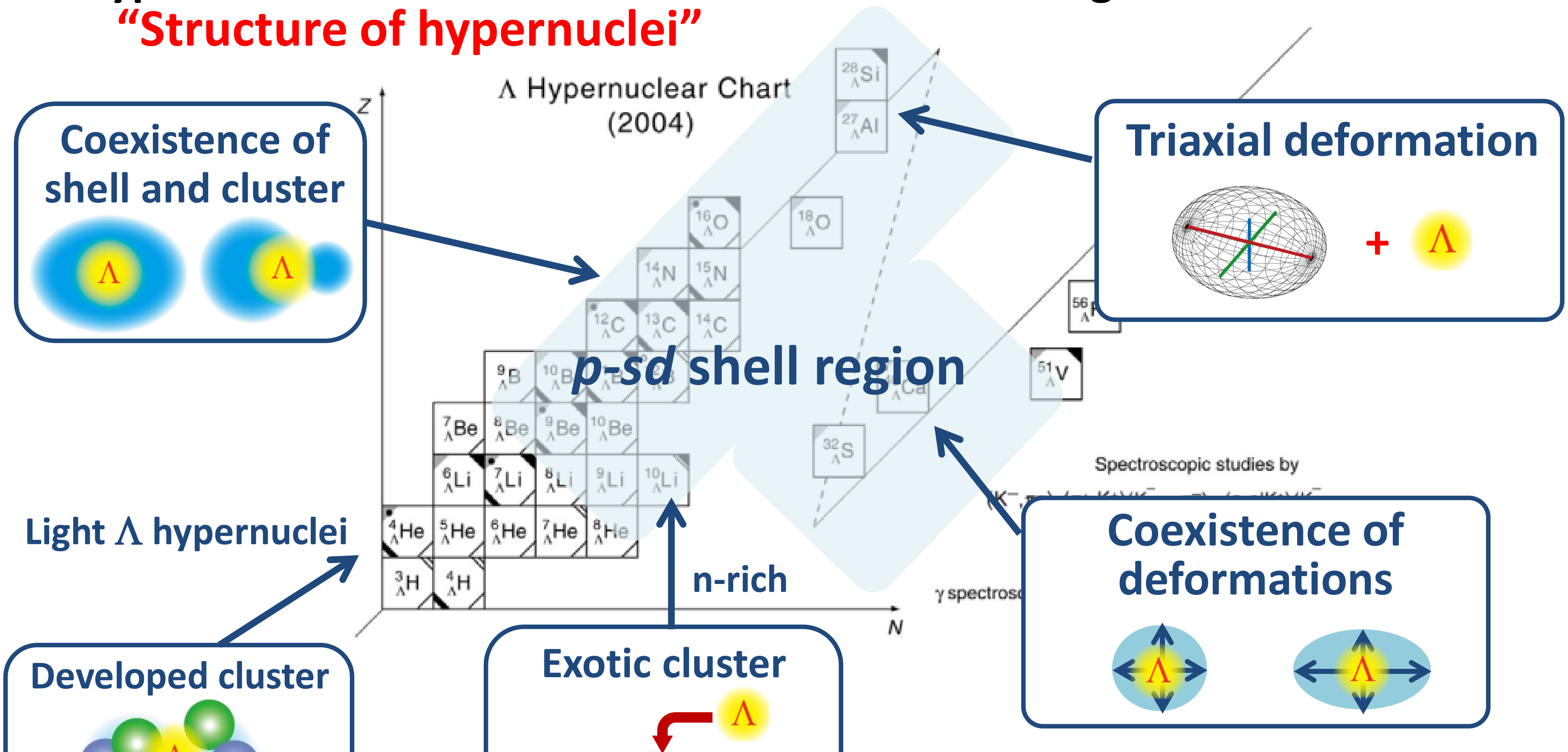
Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Toward heavier and exotic Λ hypernuclei

Experiments at JLab and J-PARC 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

Purpose of this study

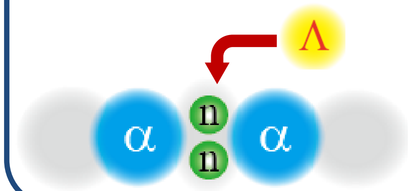
◆ Purpose

- **To reveal structure of Λ hypernuclei in *p-sd* shell and n-rich region**
  - "Structure change"
  - "Λ as a probe to study nuclear structure"

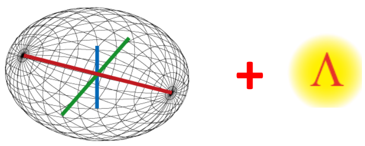
◆ Individual problems (In this talk)

- **Possible structure changes caused by Λ**
  - Deformation change by adding Λ
  - Structure of n-rich Be
- **Probing nuclear deformation by using Λ**
  - ${}^{27}{}_{\Lambda}\mathrm{Mg}$: to reveal triaxial deformation of ${}^{26}\mathrm{Mg}$

Exotic cluster



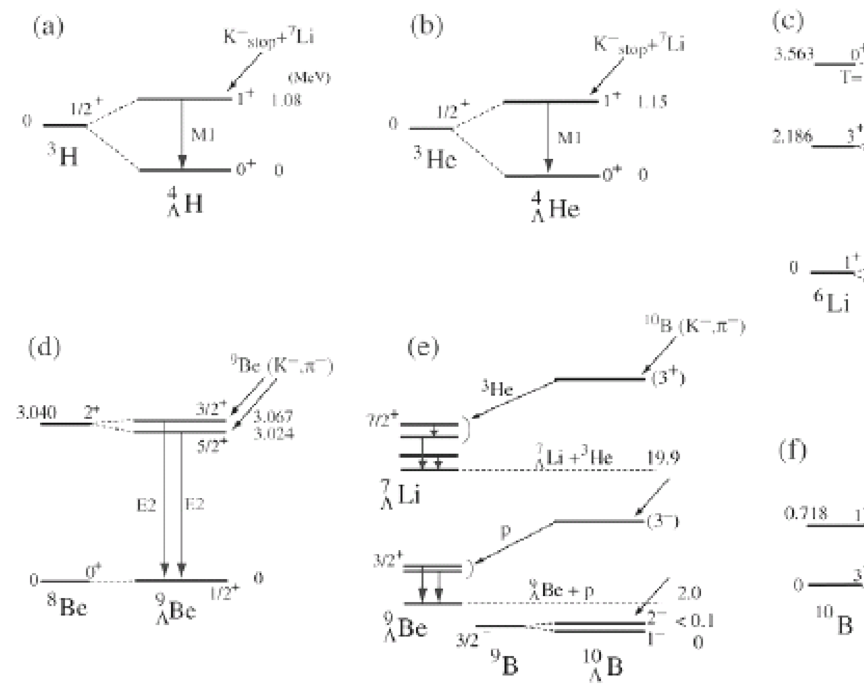
Triaxial deformation



Recent achievements in (hyper)nuclear physics

Knowledge of ΛN interaction

- **Study of light (*s*, *p*-shell) Λ hypernuclei**
  - Accurate solution of few-body problems [1]
  - ΛN G-matrix effective interactions [2]
  - Increases of experimental information [3]



Development of theoretical models

- **Through the study of unstable nuclei**

  Ex.: Antisymmetrized Molecular Dynamics (AMD)[4]
  - AMD can describe dynamical changes of various structure
  - No assumption on clustering and deformation

Recent developments enable us to study structure of Λ hypernuclei

[1] E. Hiyama, NPA **805** (2008), 190c, [2] Y. Yamamoto, *et al.*, PTP Suppl. **117** (1994), 361.,
[3] O. Hashimoto and H. Tamura, PPNP **57** (2006), 564., [4] Y. Kanada-En'yo *et al.*, PTP **93** (1995), 115.

Theoretical framework: HyperAMD

We extended the AMD to hypernuclei

HyperAMD (Antisymmetrized Molecular Dynamics for hypernuclei)

◆Hamiltonian

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

NN : Gogny D1S
ΛN : YNG interaction

◆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. :**

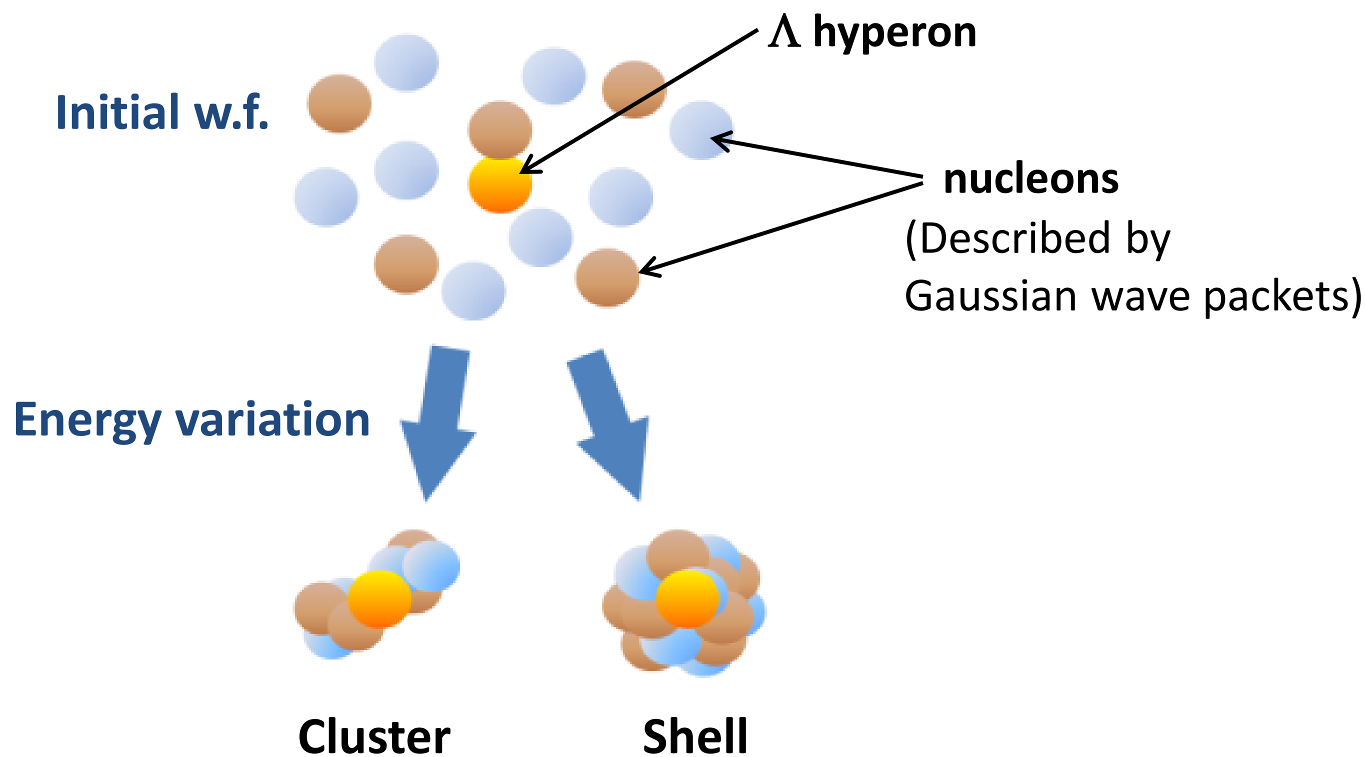
$$\psi(\vec{r}) = \sum_m c_m \varphi_m(r_\Lambda) \otimes \frac{1}{\sqrt{A!}} \det\left[\varphi_i(\vec{r}_j)\right]$$

Theoretical framework: HyperAMD

◆ Procedure of the calculation

Variational Calculation

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



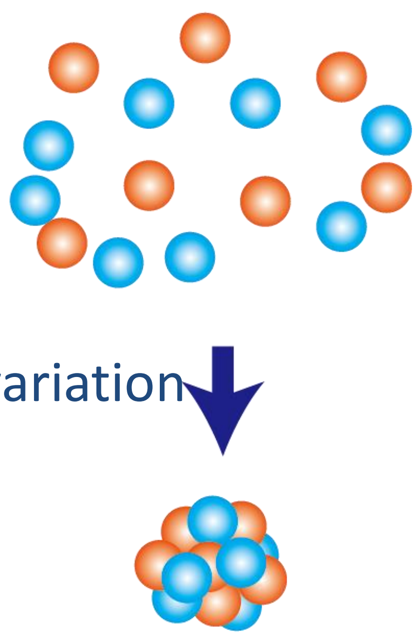
Actual calculation of HyperAMD

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

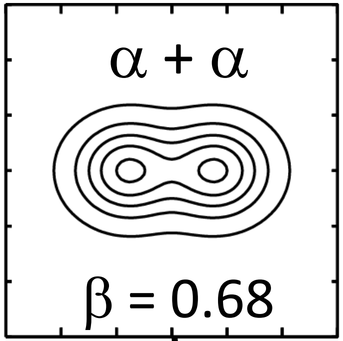
Energy variation with constraint on nuclear quadrupole deformation

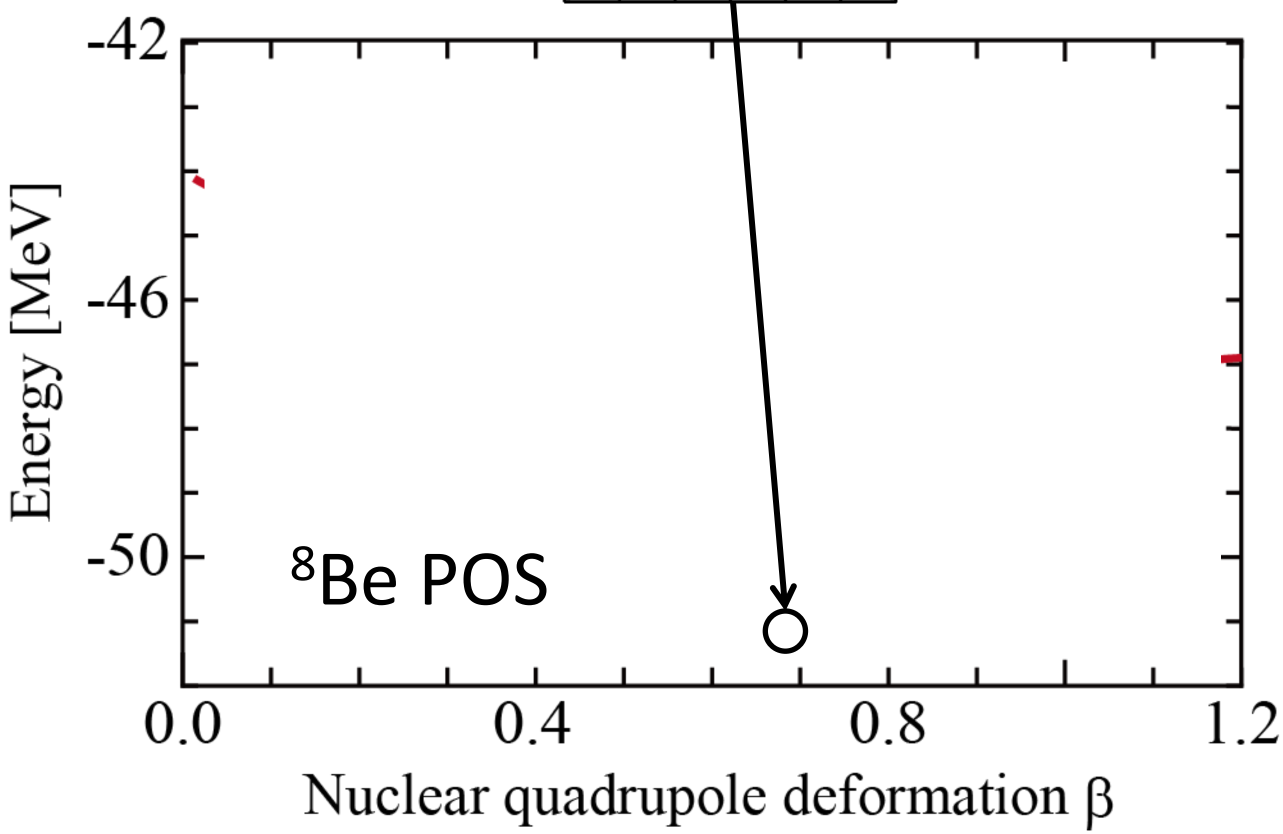
Ex.) ^{8}Be

Initial w.f.



w/o constraint on β





Actual calculation of HyperAMD

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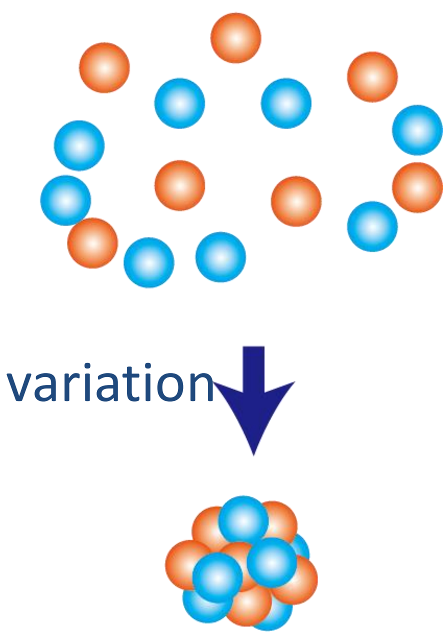
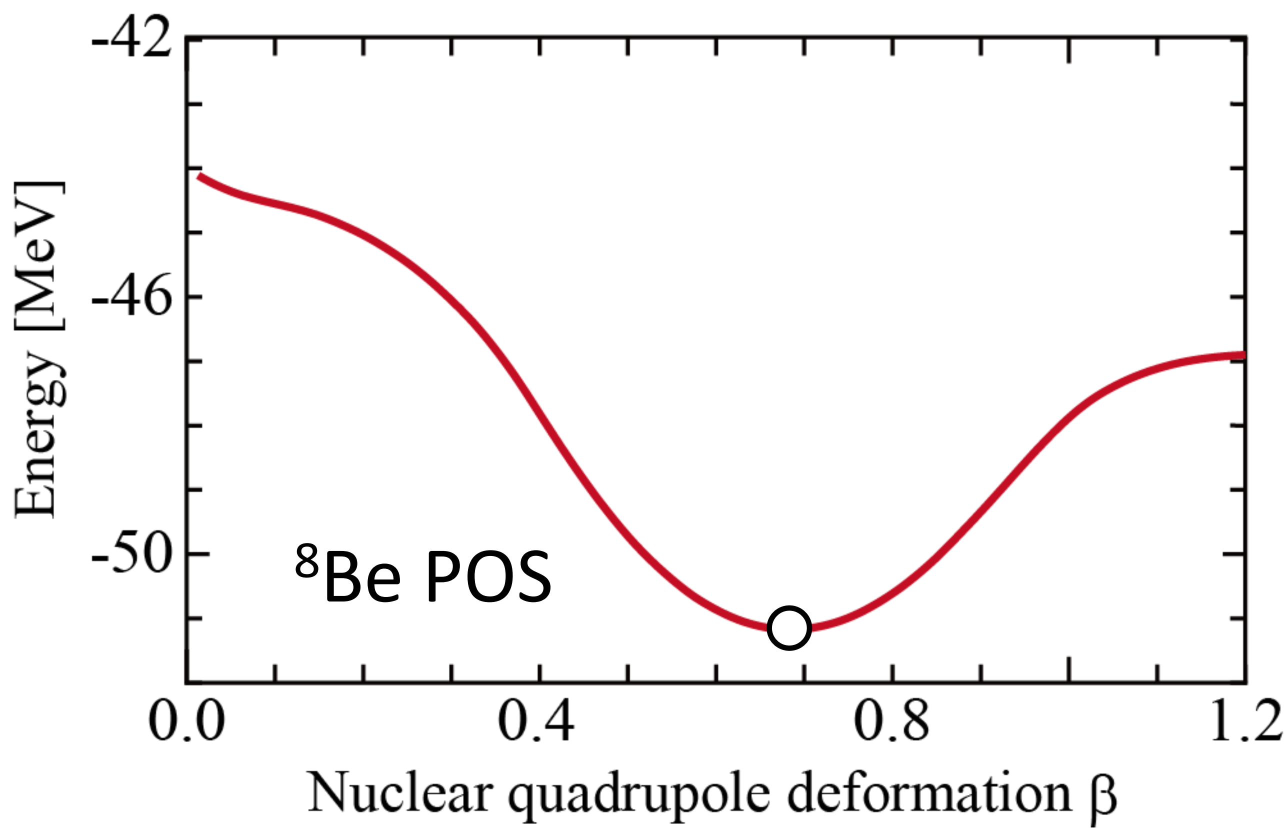
Energy variation with constraint on nuclear quadrupole deformation

Ex.) ^{8}Be

with constraint on β

Initial w.f.





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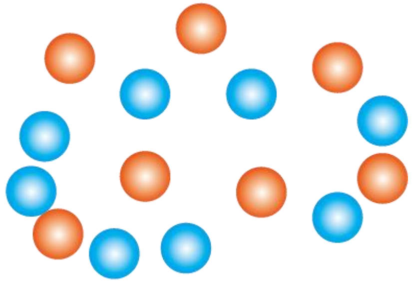
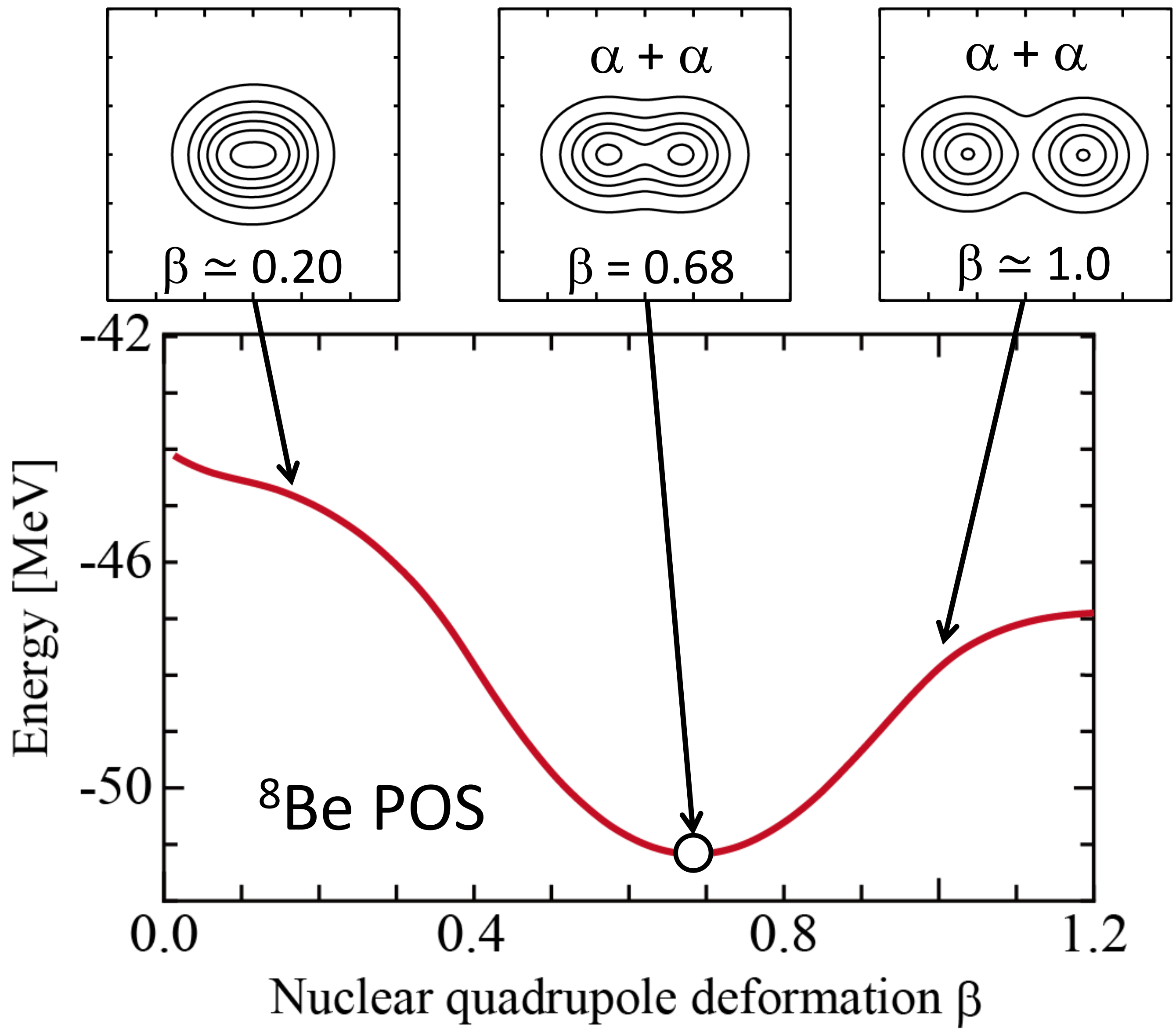
Energy variation with constraint on nuclear quadrupole deformation

Ex.) ^{8}Be

Initial w.f.



variation



Actual calculation of HyperAMD

M.Isaka, *et al.*, PRC**83**(2011) 044323
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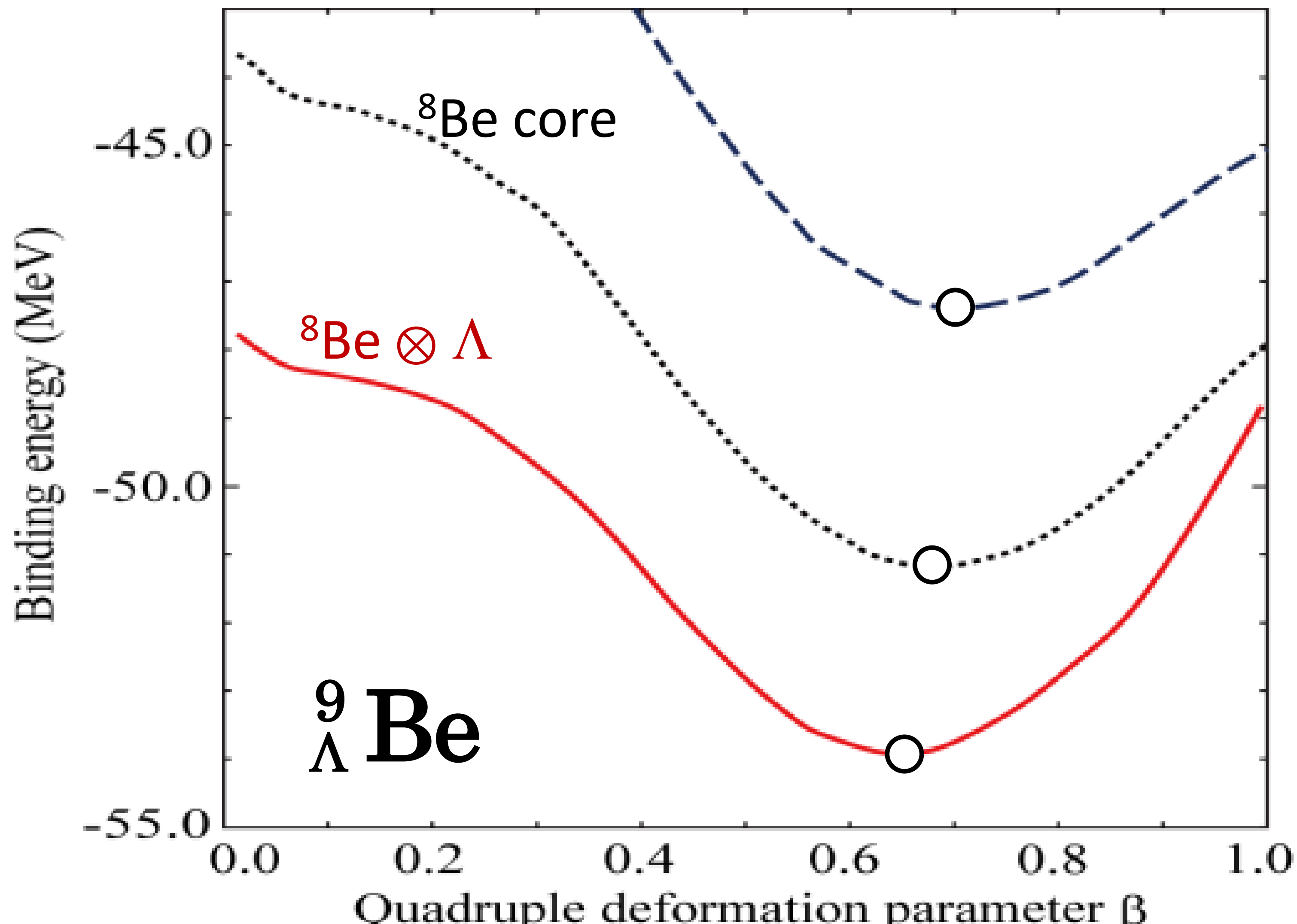
◆ For hypernuclei



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: $X_i = Z_i, z_i, \alpha_i, \beta_i, a_i, b_i, \nu_i, c_i$

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)

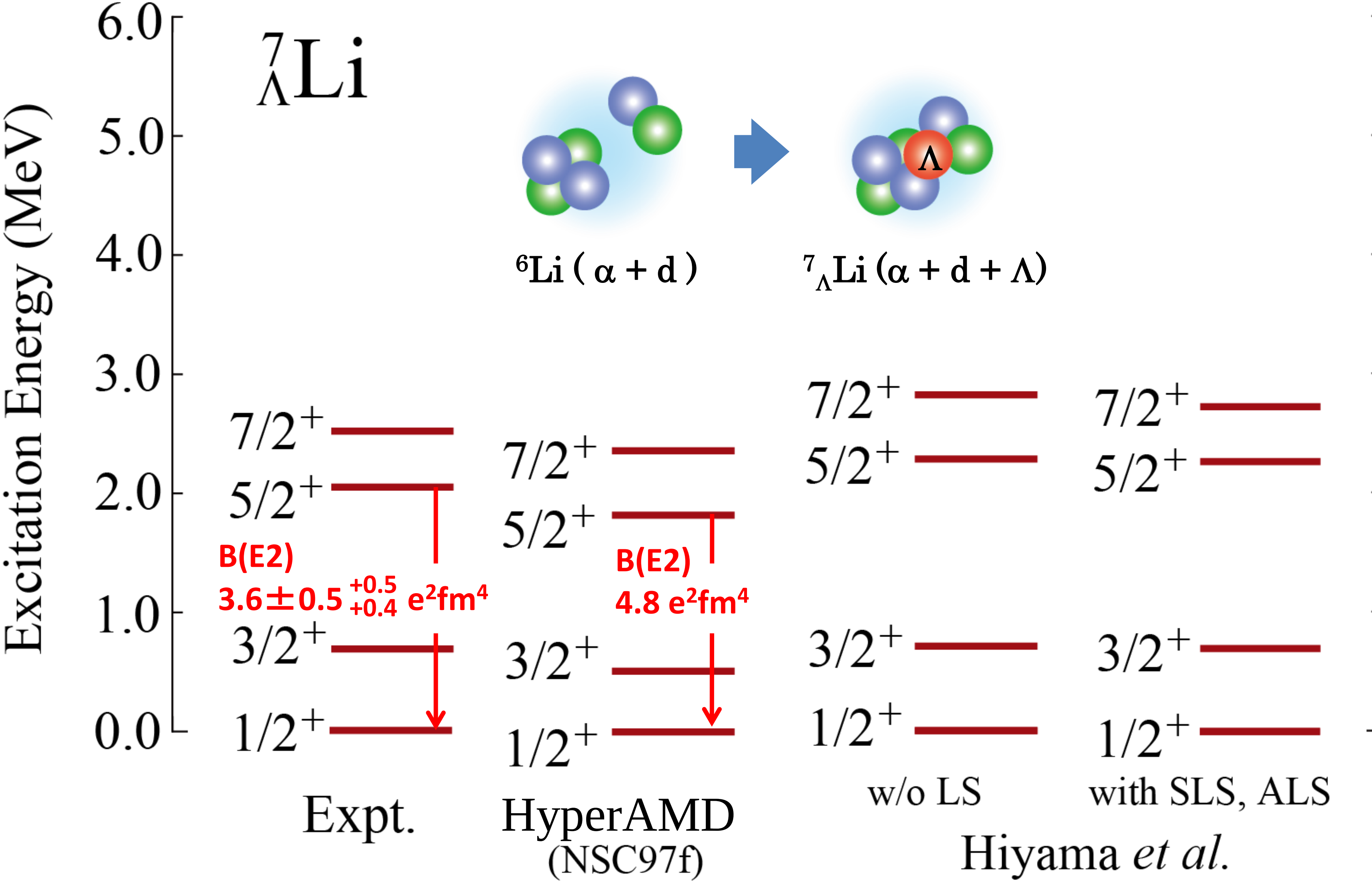
- Superposition of the w.f. with different configuration
- Diagonalization of $H_{sK,s'K'}^{J\pm}$ and $N_{sK,s'K'}^{J\pm}$

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

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

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

Application of HyperAMD to $^{7}_{\Lambda}$Li



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

E. Hiyama, *et al.*, PRC **74**, 054312 (2006)

Structure change by Λ

- **Nuclear deformation change by Λ (in *s* and *p* orbits)**

  Examples: ${}^{9}_{\Lambda}$Be, ${}^{13}_{\Lambda}$C, ${}^{20}_{\Lambda}$Ne and ${}^{21}_{\Lambda}$Ne   M. Isaka, et. al., PRC **83** (2011), 044323.

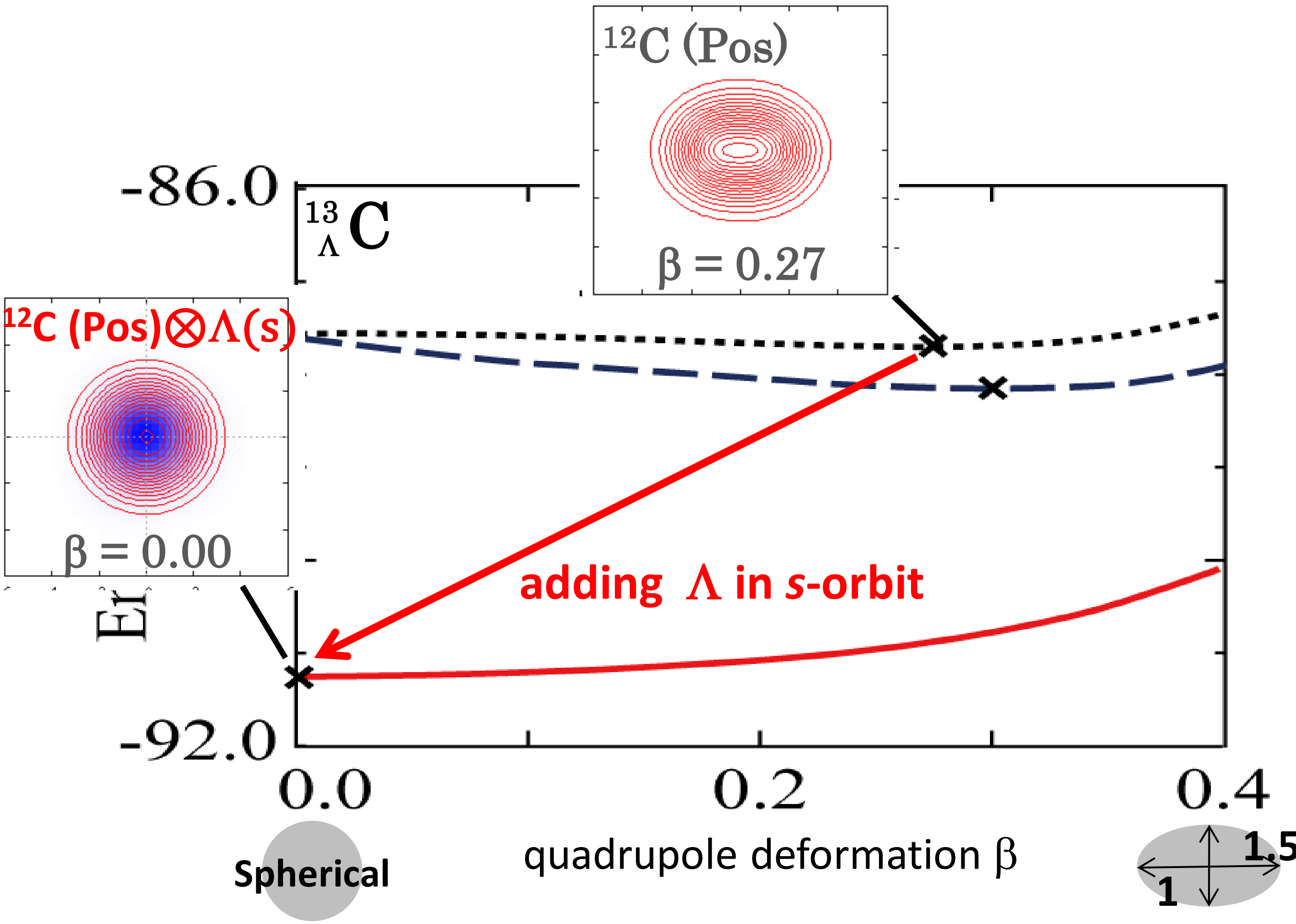
- **Structure change of neutron-rich Be**

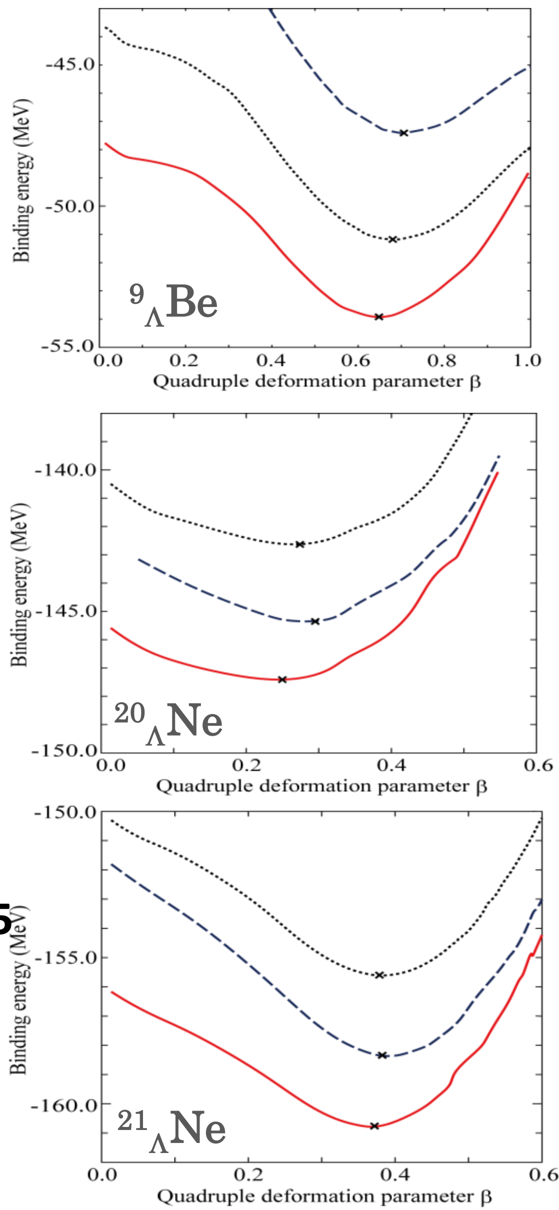
  Changes of the level structure in ${}^{12}_{\Lambda}$Be

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

Deformation change by Λ in *s*-orbit

- **From changes of energy curves**

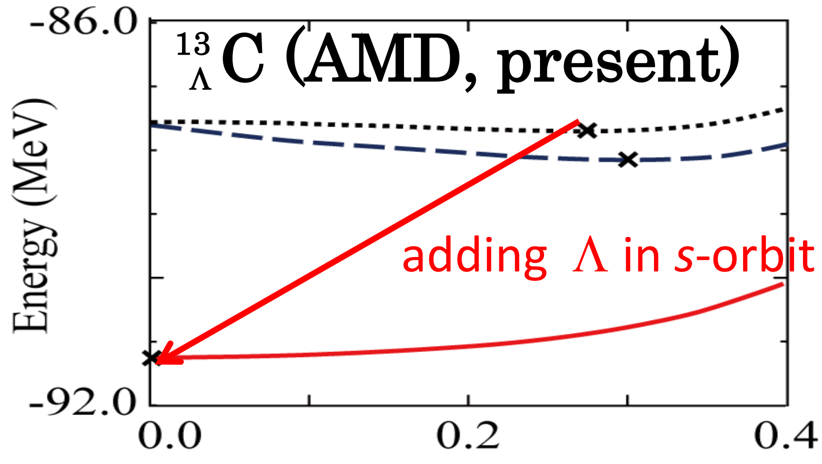




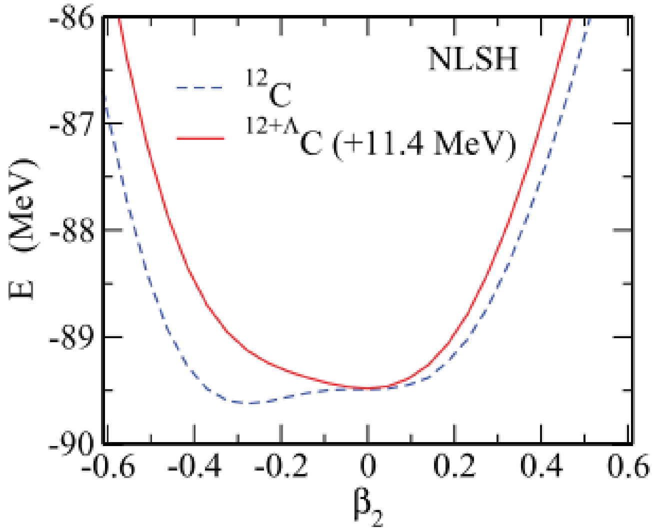
Λ in *s*-orbit reduces the nuclear deformation

Deformation change by Λ in *s*-orbit

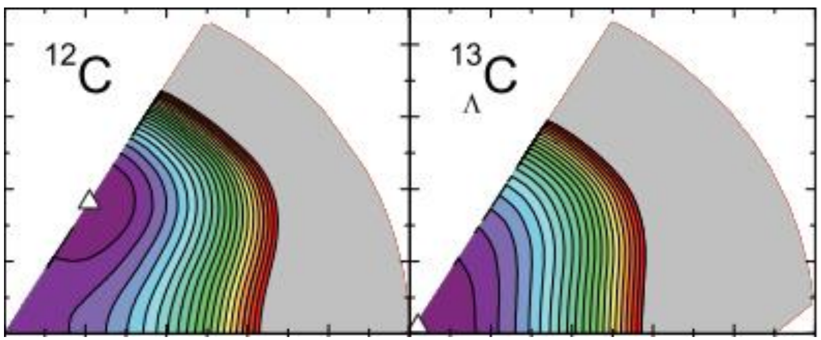
- **Many authors predict the deformation change by Λ in *s*-orbit**



Ex.) Deformation change in $^{13}{}_{\Lambda}$C predicted by RMF calc.



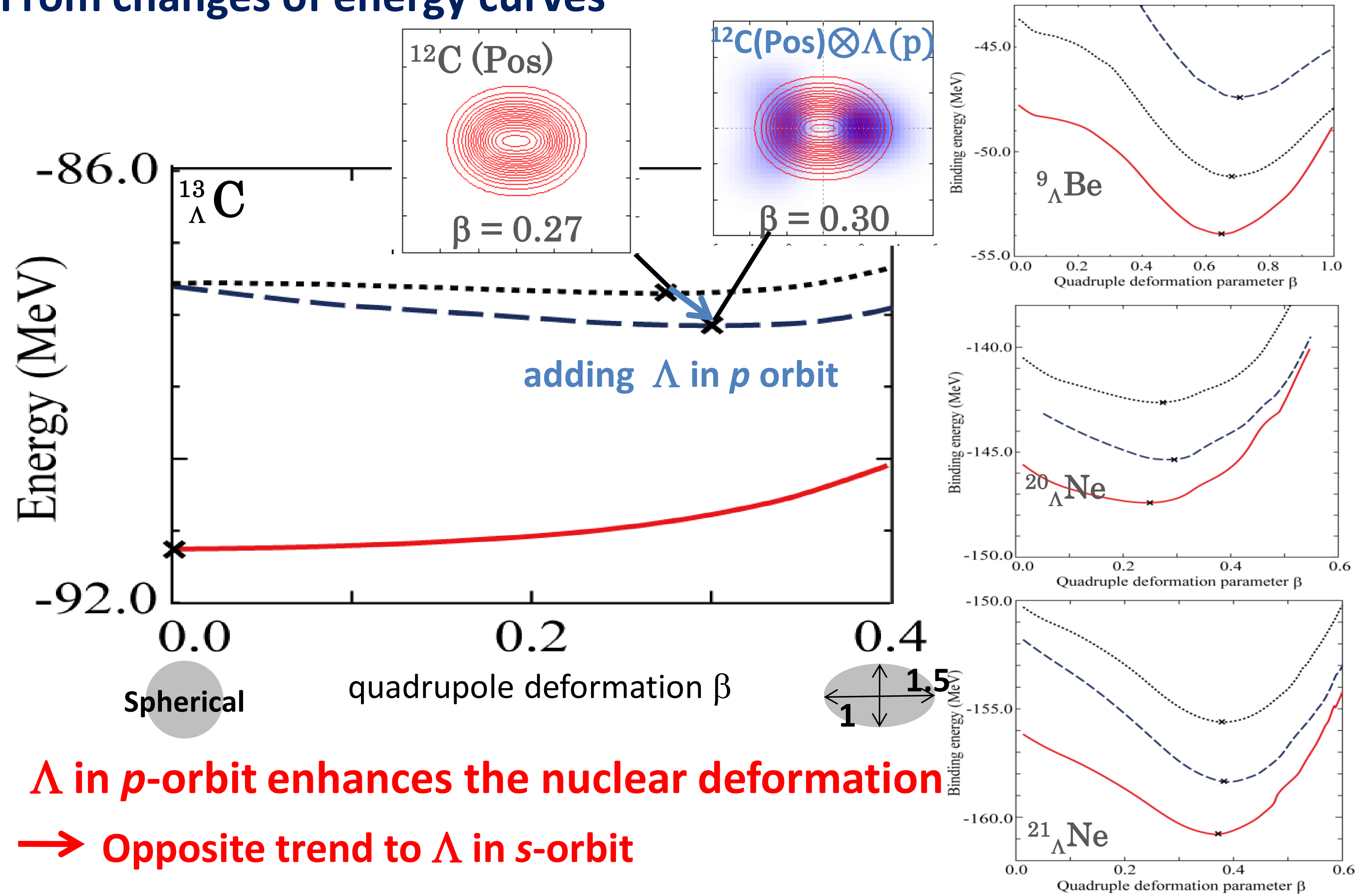
M. T. Win and K. Hagino, Phys. Rev. C **78**, 054311(2008)



Bing-Nan Lu, et al., Phys. Rev. C **84**, 014328 (2011)

Deformation change by Λ in *p*-orbit

◆ **From changes of energy curves**



Λ in *p*-orbit enhances the nuclear deformation

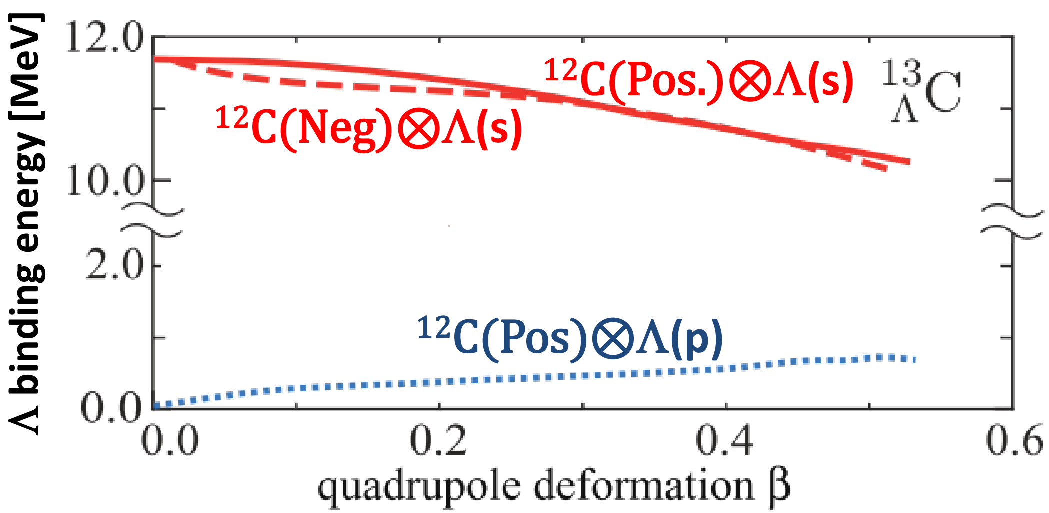
→ Opposite trend to Λ in *s*-orbit

Λ binding energy

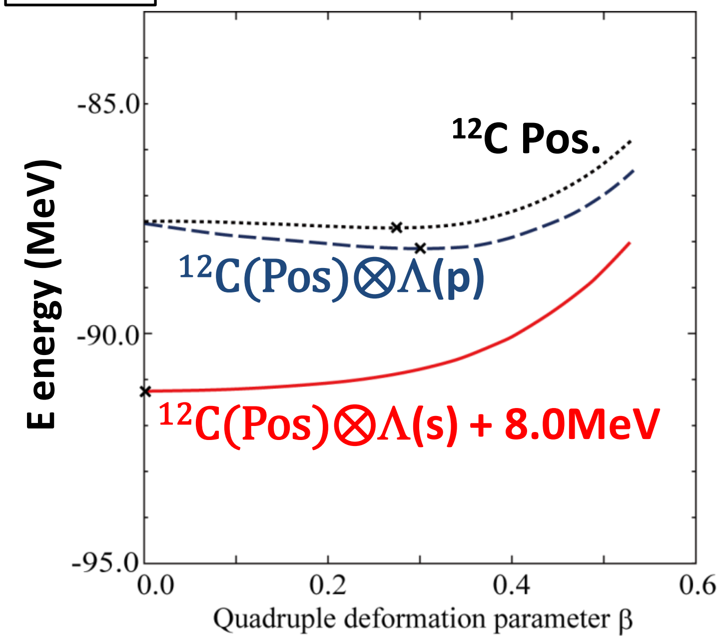
◆ Variation of the Λ binding Energy

- Λ in *s*-orbit is deeply bound at smaller deformation
- Λ in *p*-orbit is deeply bound at larger deformation

$^{13}_{\Lambda}C$ Binding energy of Λ



$^{13}_{\Lambda}C$ Energy curves



Variation of the Λ binding energies causes the deformation change (reduction or enhancement)

Structure change by Λ

- **Nuclear deformation change by Λ (in *s* and *p* orbits)**

  Examples: $^{9}_{\Lambda}$Be, $^{13}_{\Lambda}$C, $^{20}_{\Lambda}$Ne and $^{21}_{\Lambda}$Ne   M. Isaka, et. al., PRC **83** (2011), 044323.

- **Structure change of neutron-rich Be**

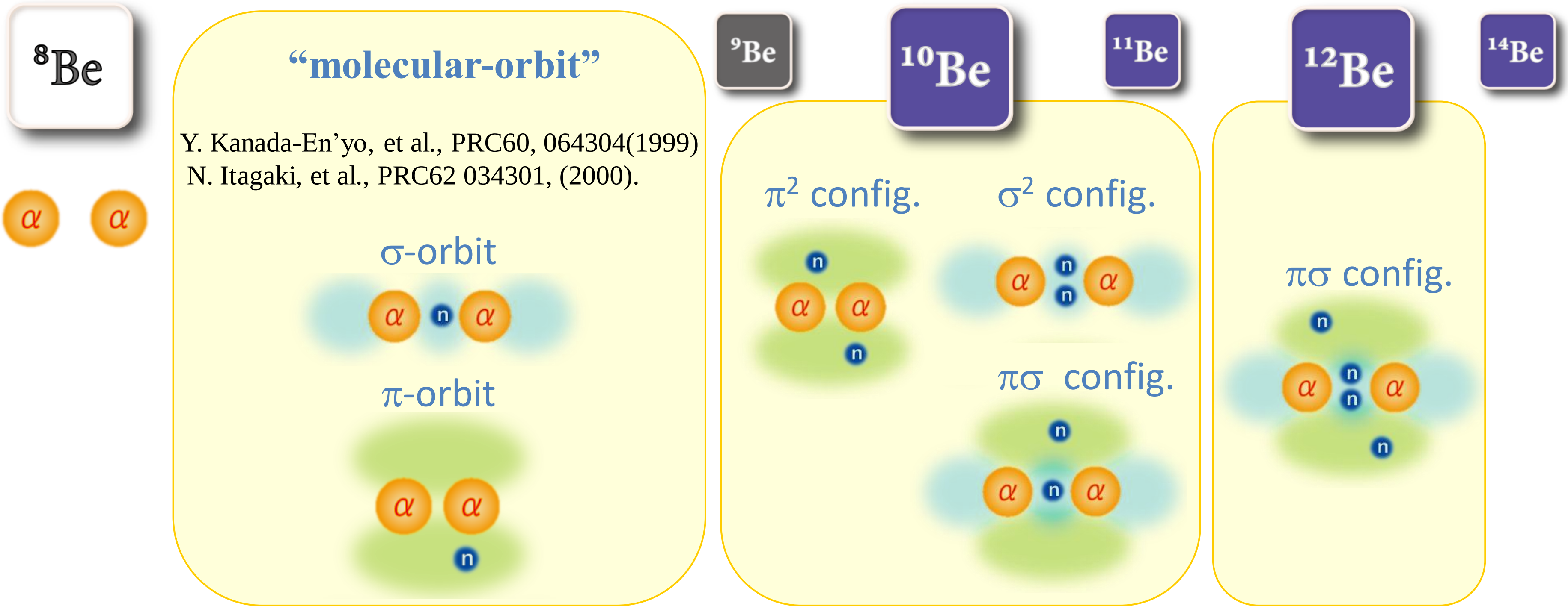
  Changes of the level structure in $^{12}_{\Lambda}$Be

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

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

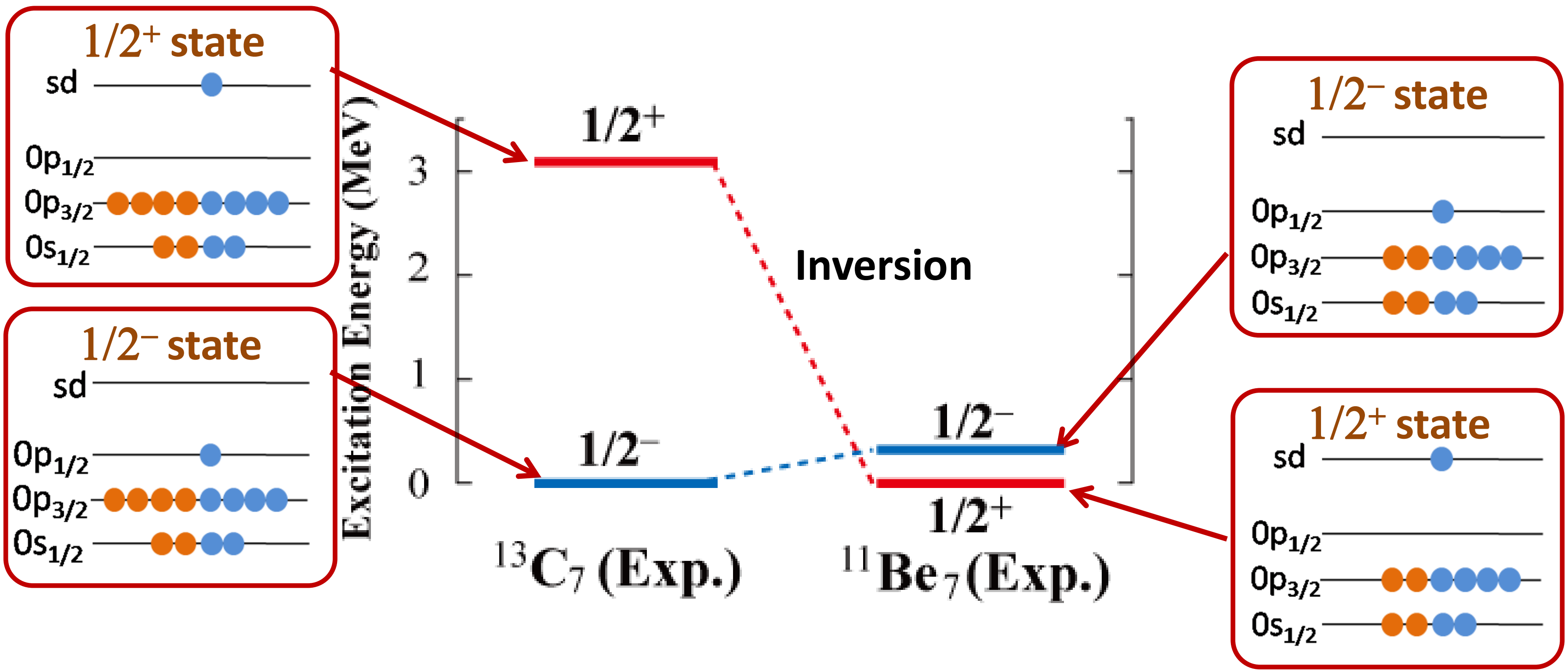


What is happen by adding a Λ to these exotic cluster structure ?

Exotic structure of ^{11}Be

◆ **Parity inverted ground state of the $^{11}_{4}\mathrm{Be}_7$**

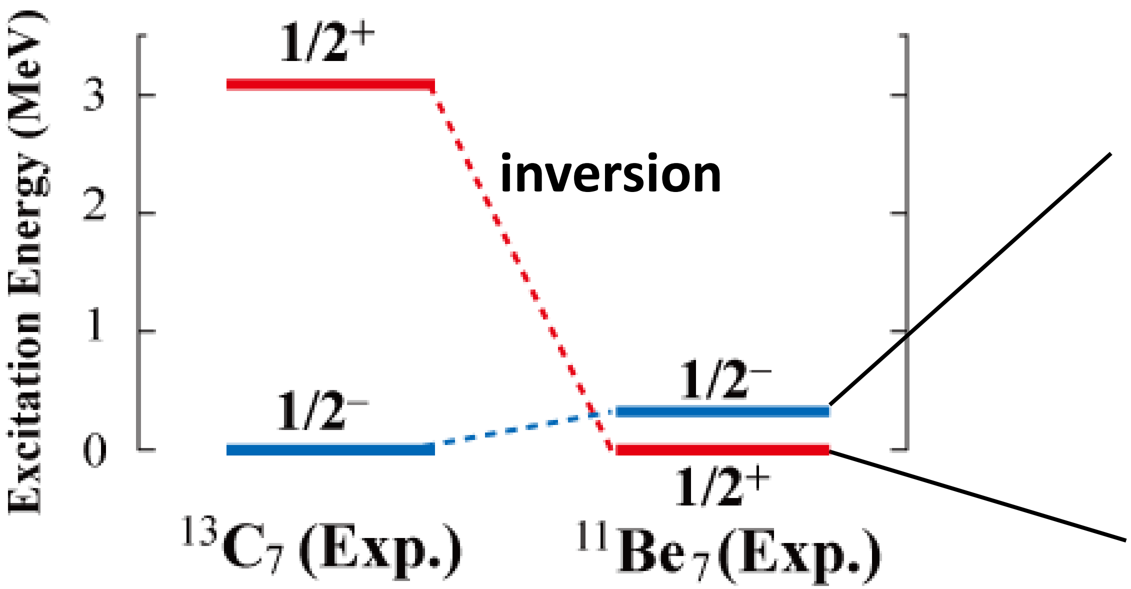
- **The ground state of ^{11}Be is $1/2^+$,**
  while ordinary nuclei have a $1/2^-$ state as the ground state
  → **Vanishing of the magic number N=8**

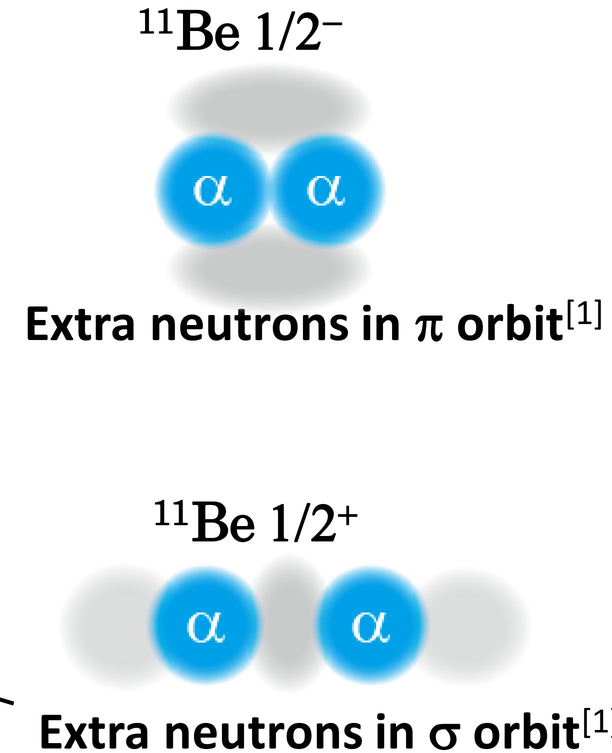


Exotic structure of ^{11}Be

◆ Parity inversion of the $^{11}Be_7$ ground state

- **The ground state of ^{11}Be is $1/2^+$**



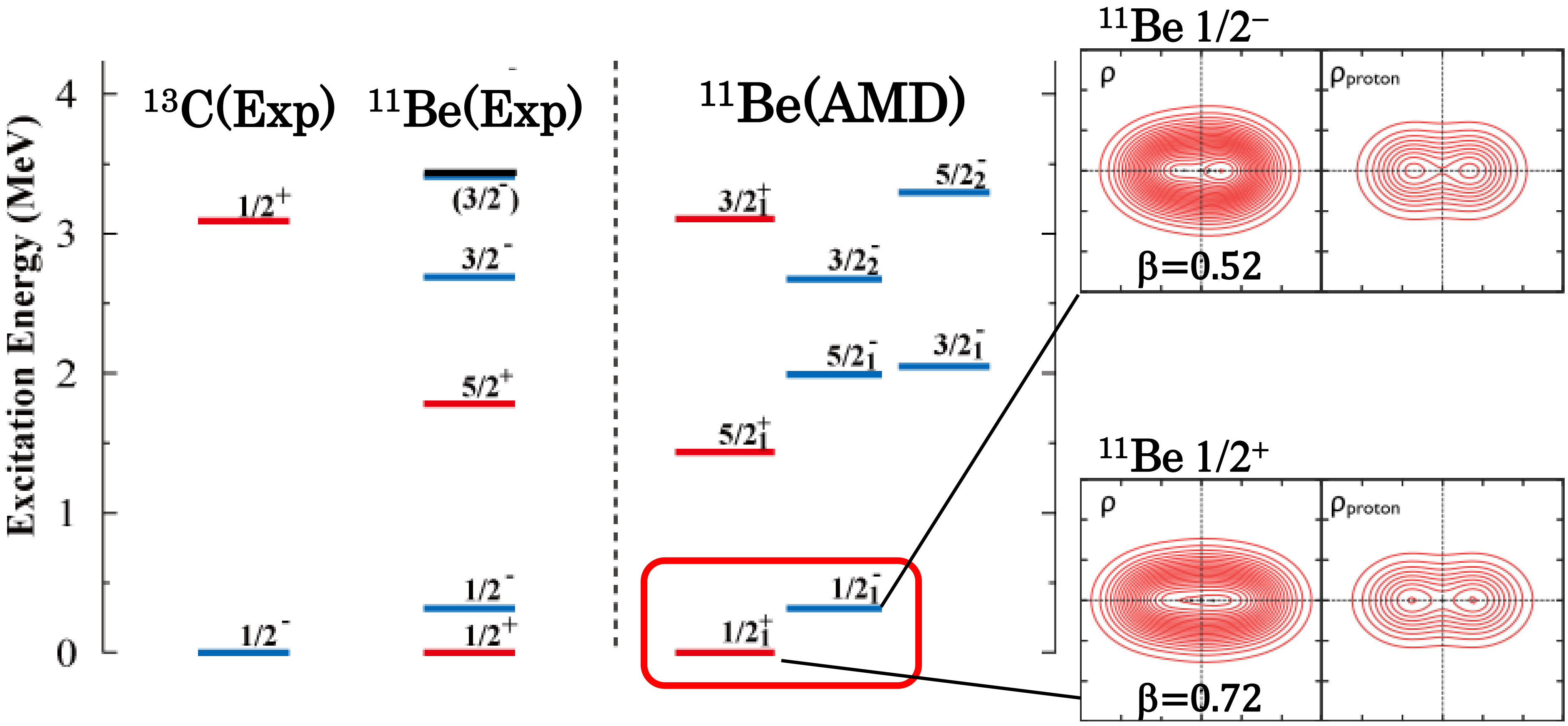


- **Main reason of the parity inversion: molecular orbit structure**
- **^{11}Be has 2α clusters with 3 surrounding neutrons**

⟶ Extra neutrons occupy molecular orbits around the 2α cluster

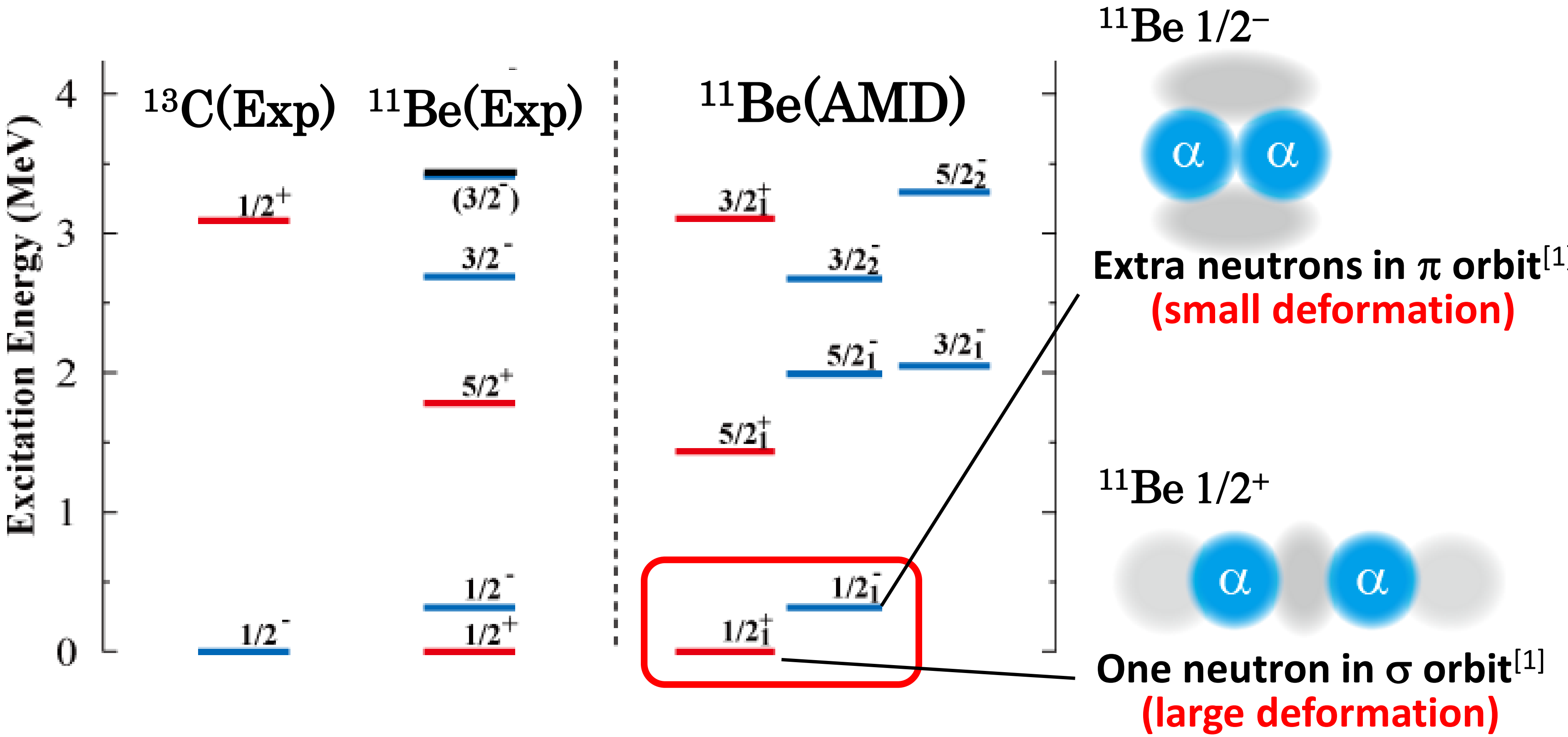
[1] Y. Kanada-En'yo and H. Horiuchi, PRC **66** (2002), 024305.

Excitation spectra of ^{11}Be



- **Deformation of the 1/2$^-$ state is smaller than that of the 1/2$^+$ state**

Excitation spectra of ^{11}Be

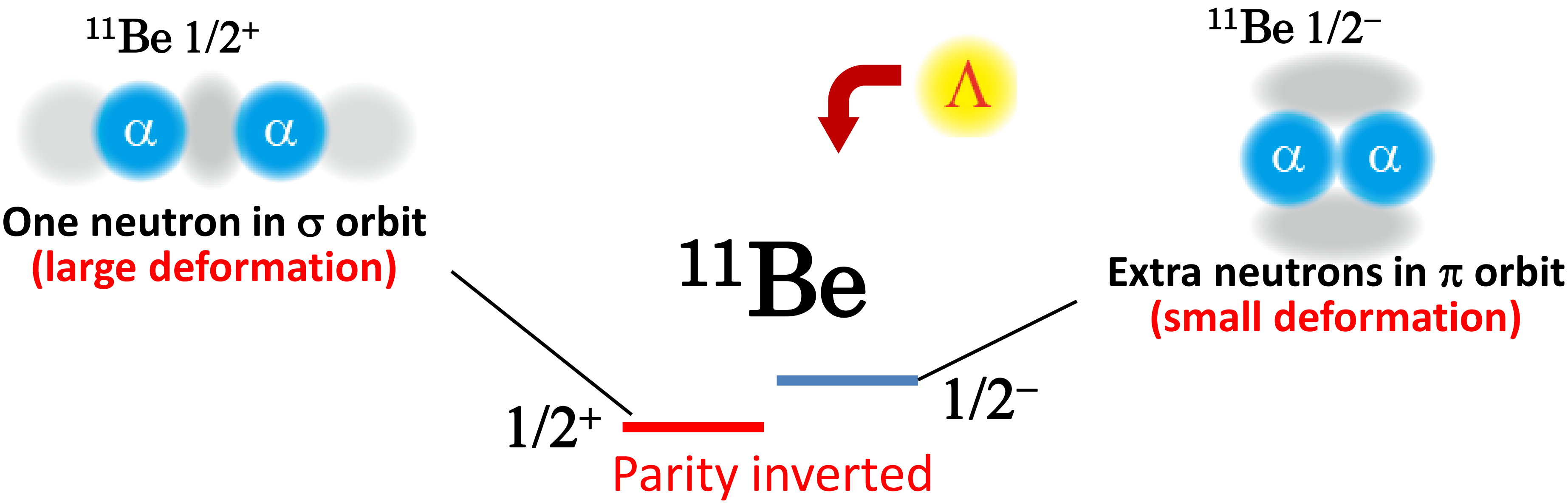


- **Deformation of the 1/2$^-$ state is smaller than that of the 1/2$^+$ state**

↑ Difference in the orbits of extra neutrons

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

Structure change in $^{12}_{\Lambda}$Be

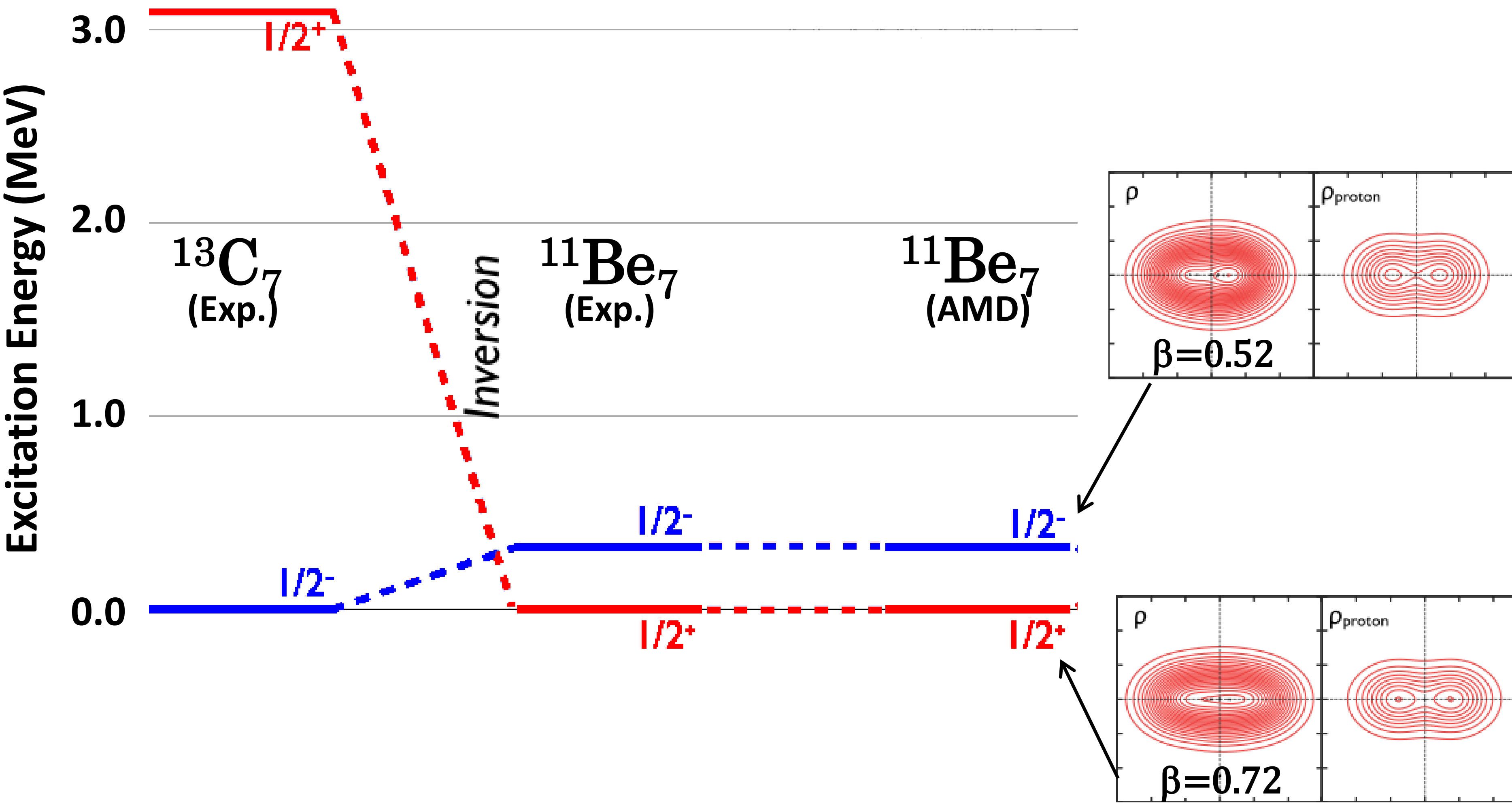


What is happen by Λ in these states with different deformations?

Deformations are reduced?
Parity-inverted ground state changes?

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

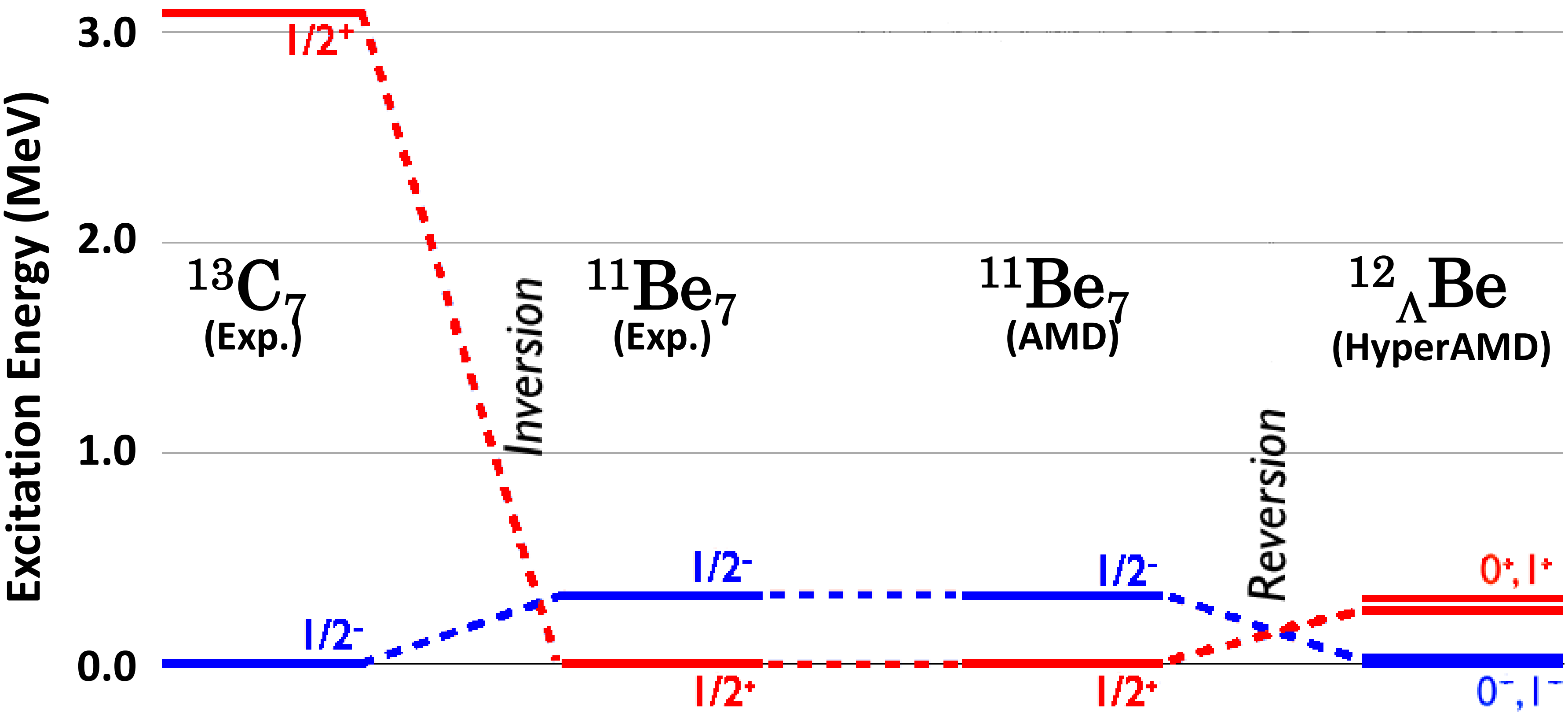
◆ **Ground state of $^{12}{}_{\Lambda}$Be**



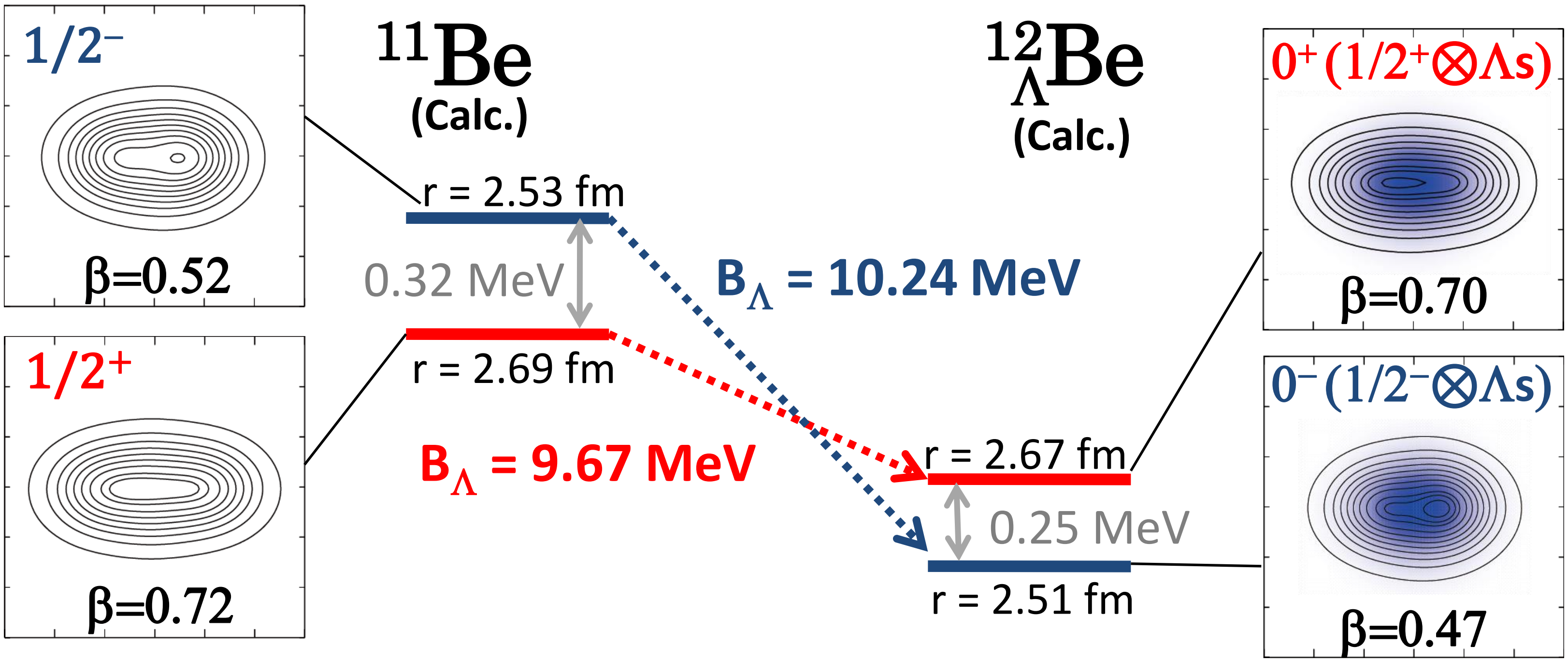
Results: Parity reversion of $^{12}{}_{\Lambda}$Be

◆ 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

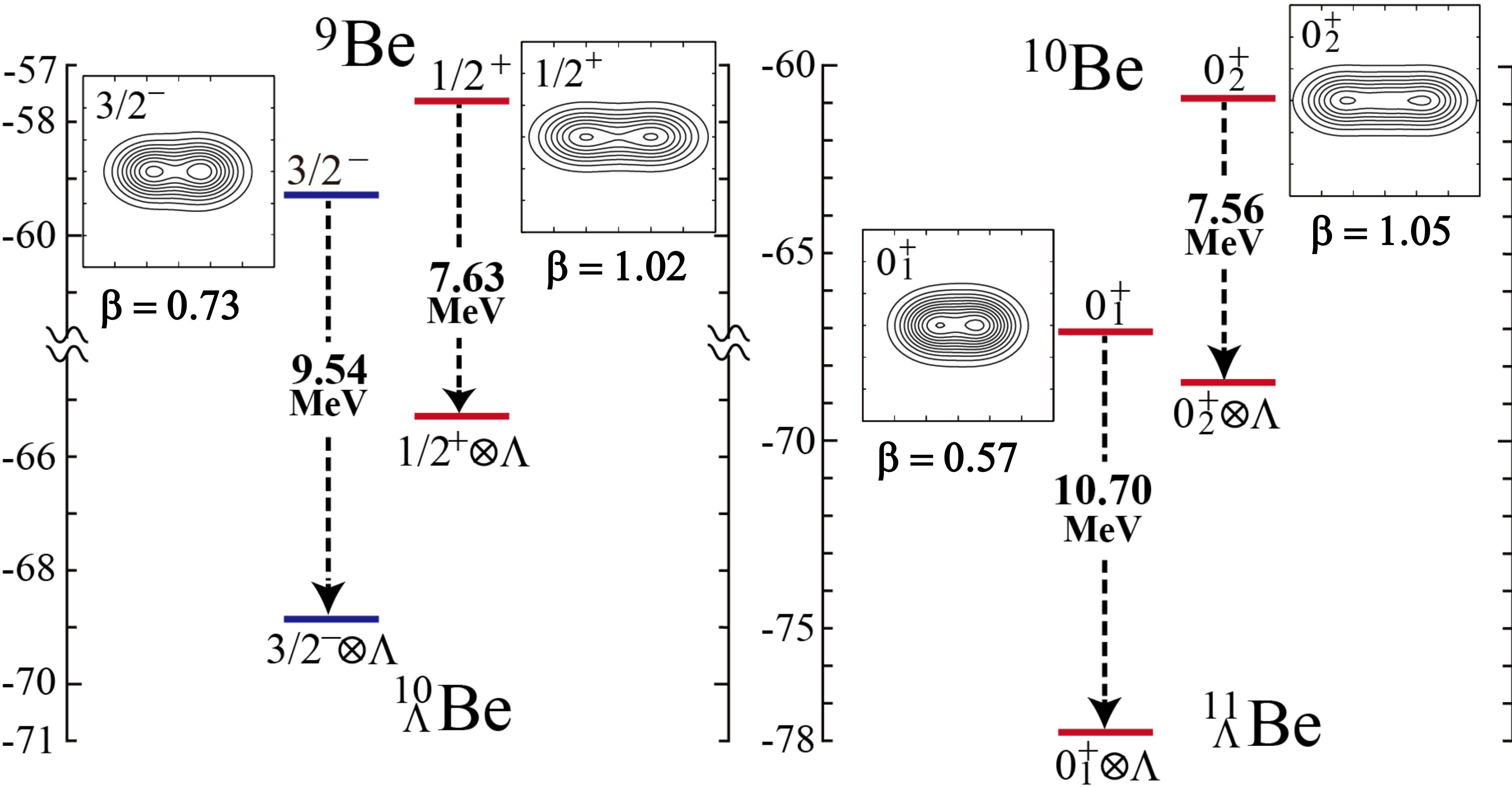


- **Λ slightly reduces deformations, but the deformation is still different**
- **Λ hyperon coupled to the $1/2^-$ state is more deeply bound than that coupled to the $1/2^+$ state**
  - **Due to the difference of the deformation between the $1/2^-$ and $1/2^+$ states**

Difference of deformation in ^{11}Be can be confirmed by parity-reversion

In the other Be Λ hyper-isotopes

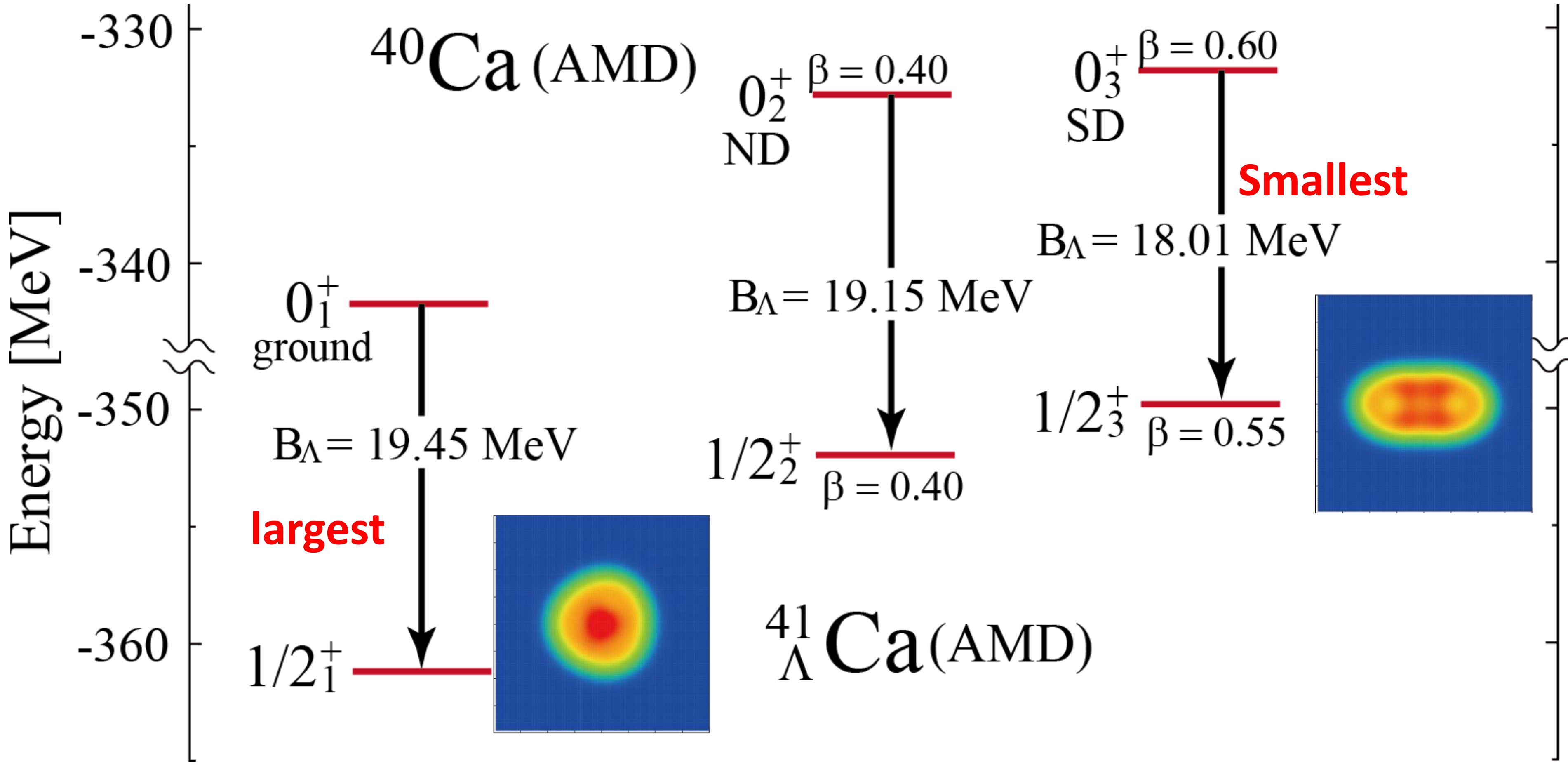
- B_Λ is different depending on deformations
- Deformations: mainly comes from developments of 2α cluster structure



M. Isaka, M. Kimura, PRC, in press

Difference of B_Λ depending on deformation

B_Λ is different among the ground, ND and SD states



M. Isaka, *et al.*, PRC**89**, 024310 (2014)

Probing nuclear deformation by using Λ

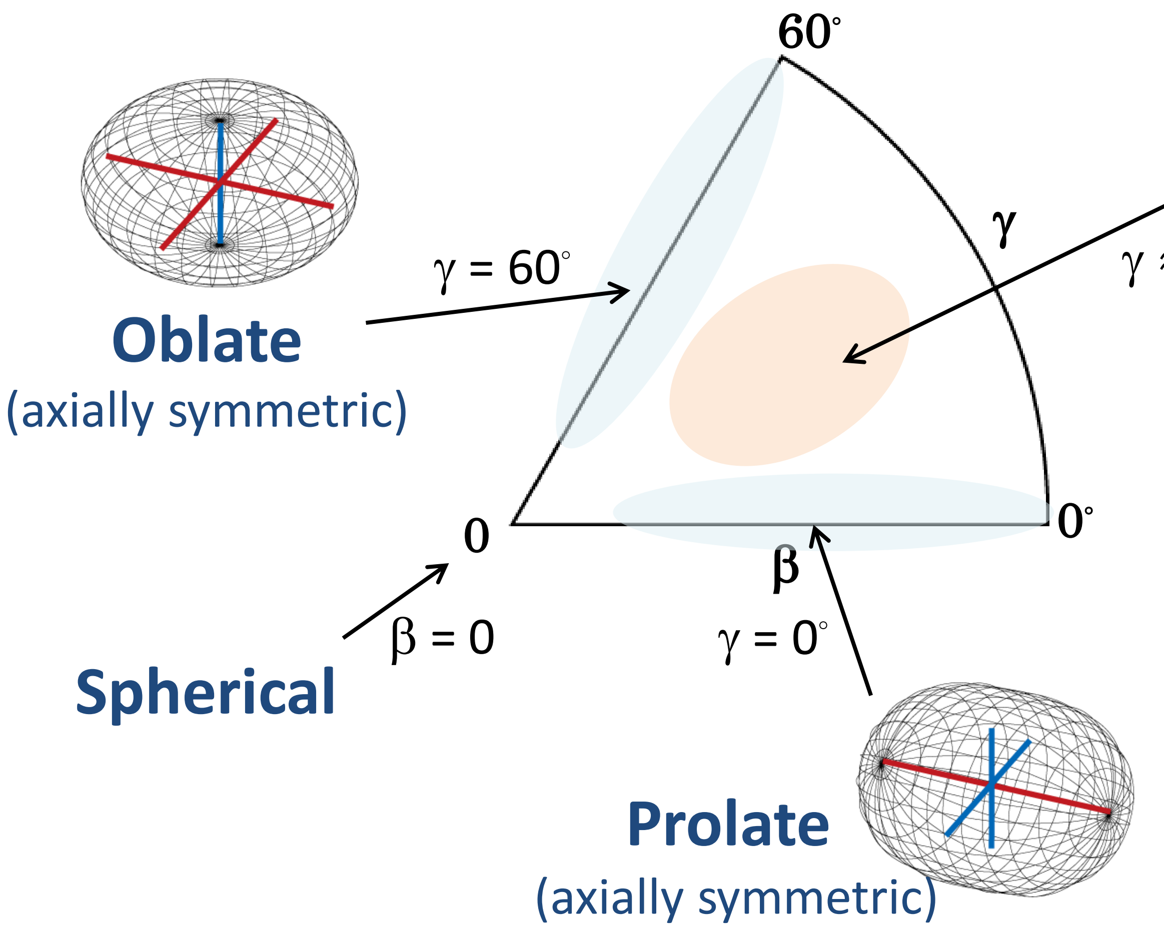
Example: Triaxial deformation of Mg

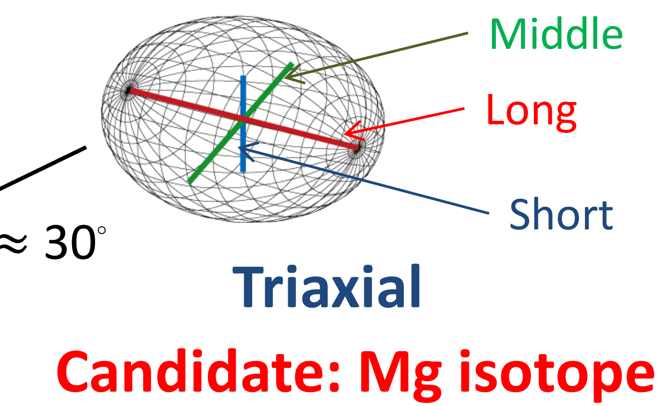
$^{25}_{\Lambda}$Mg: M. Isaka, *et al.*, PRC **87**, 021304R (2013)

$^{27}_{\Lambda}$Mg: **Recent result** $\leftarrow$ By future experiment at JLab ^{27}Al(e, e'K^{+})$^{27}_{\Lambda}$Mg ?

Deformation of nuclei

- **Many nuclei manifests various quadrupole deformation**
  (parameterized by quadrupole deformation parameters β and γ)
- **Most of them are prolate or oblate deformed (axially symmetric)**

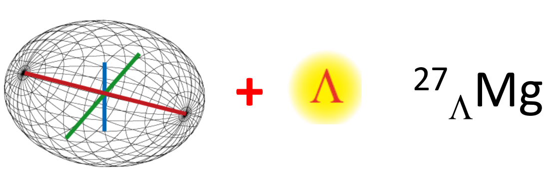




Various deformations

Today's talk:

Triaxial deformation

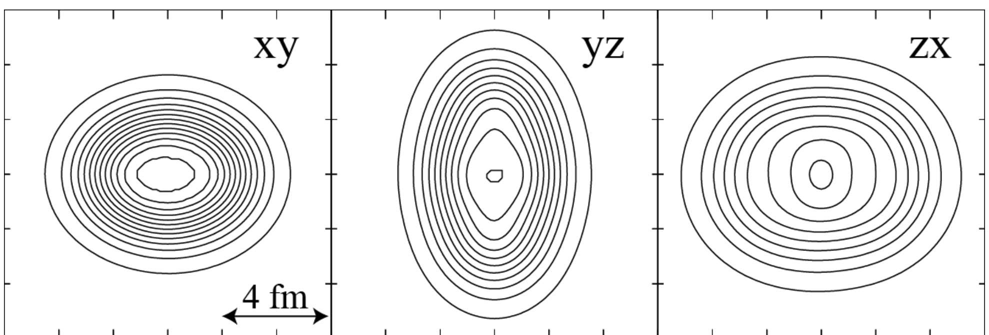


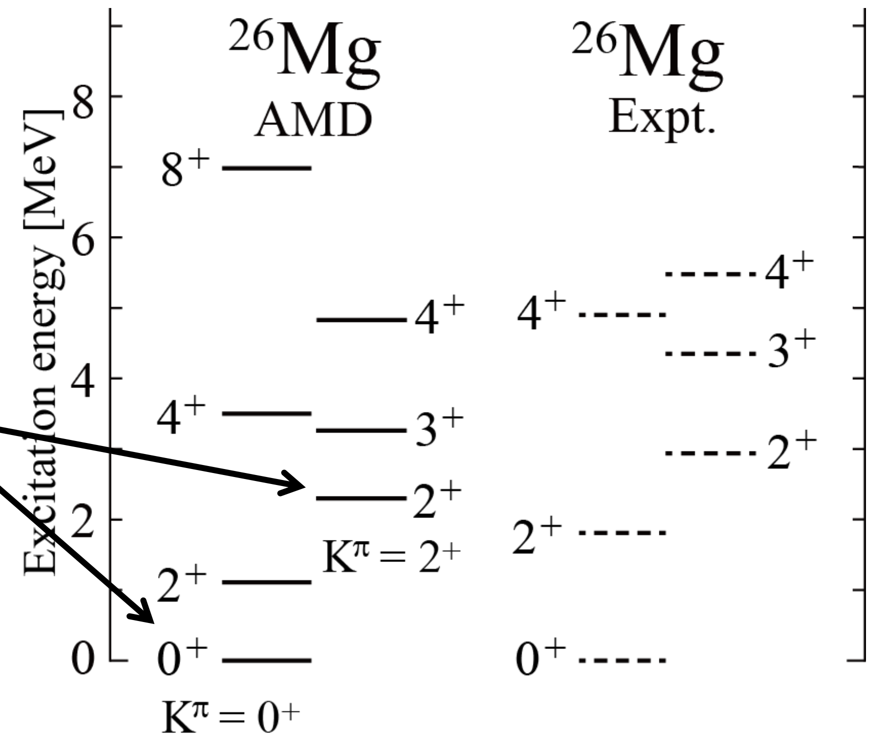
Triaxial deformation of nuclei

Triaxial deformed nuclei are not many, Mg isotopes are the candidates

Ex.) ^{24}Mg, ^{26}Mg

- Largely deformed nuclei (far from magic number)
- Low-lying 2nd 2^+ indicates having the triaxial deformation



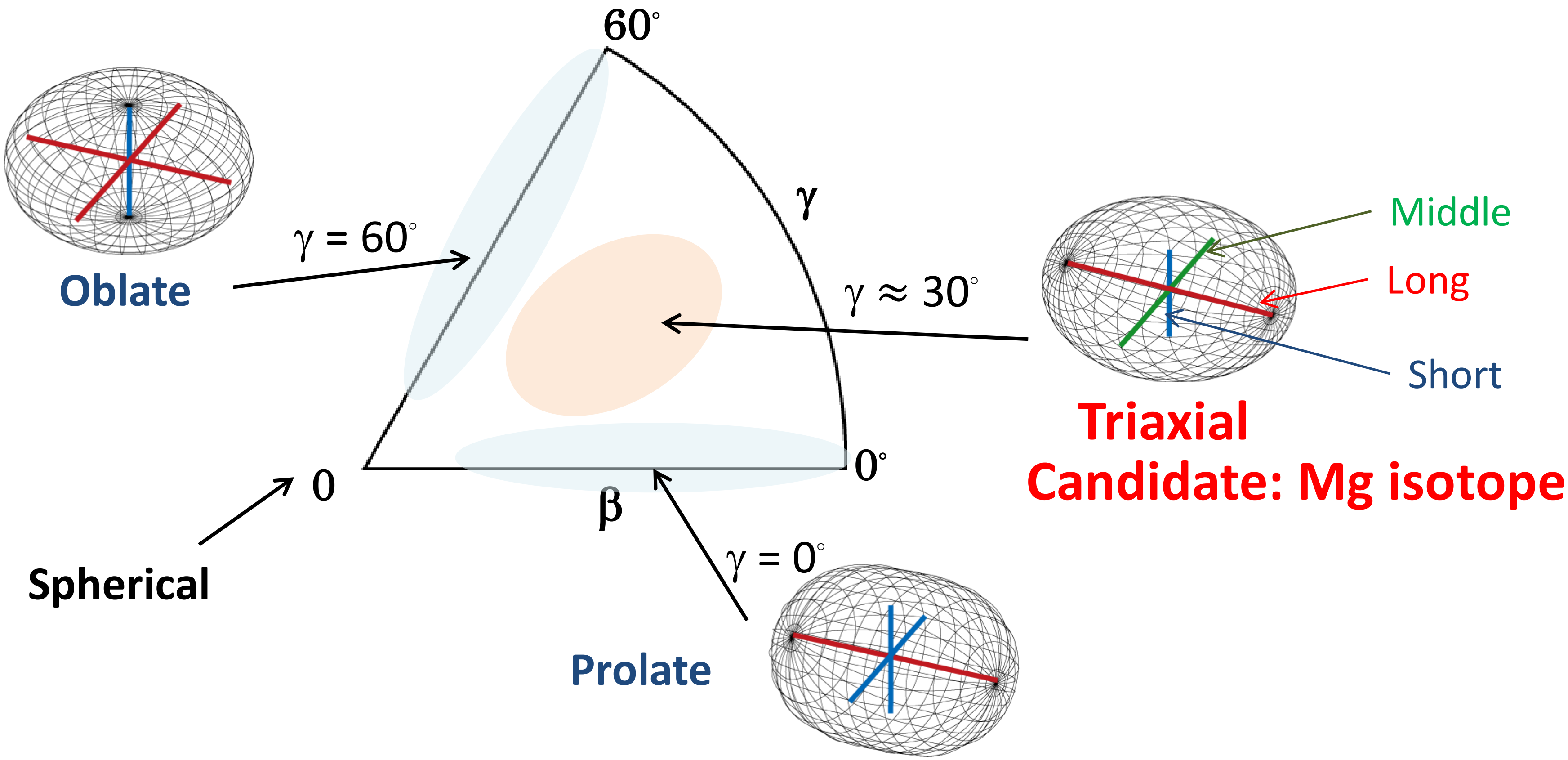


Identification of triaxial deformation is not easy

Our task: to identify triaxial deformation of ^{26}Mg by using Λ

Deformation of nuclei

- **Triaxial deformed nuclei are not many**
- **Its identification is not easy**



"Λ in *p* orbit can be a probe to study nuclear (triaxial) deformation"

What happens when a Λ in *p* orbit is coupled to triaxial deformation?

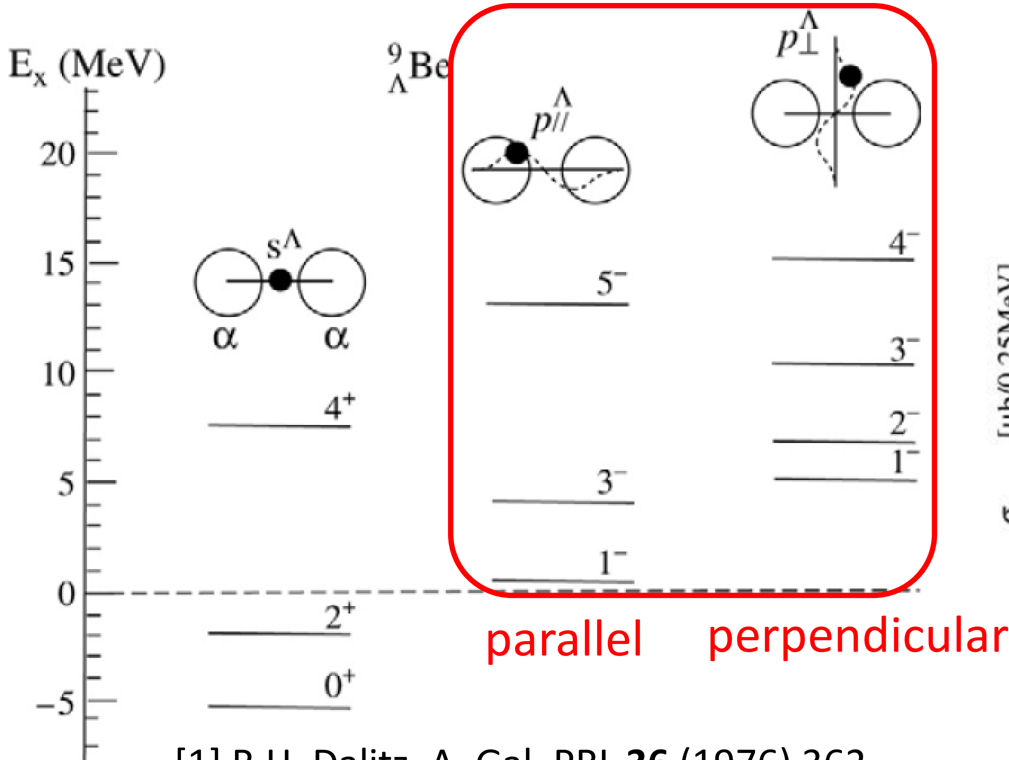
Coupling of Λ in *p*-orbit: *p*-states of $^{9}_{\Lambda}$Be

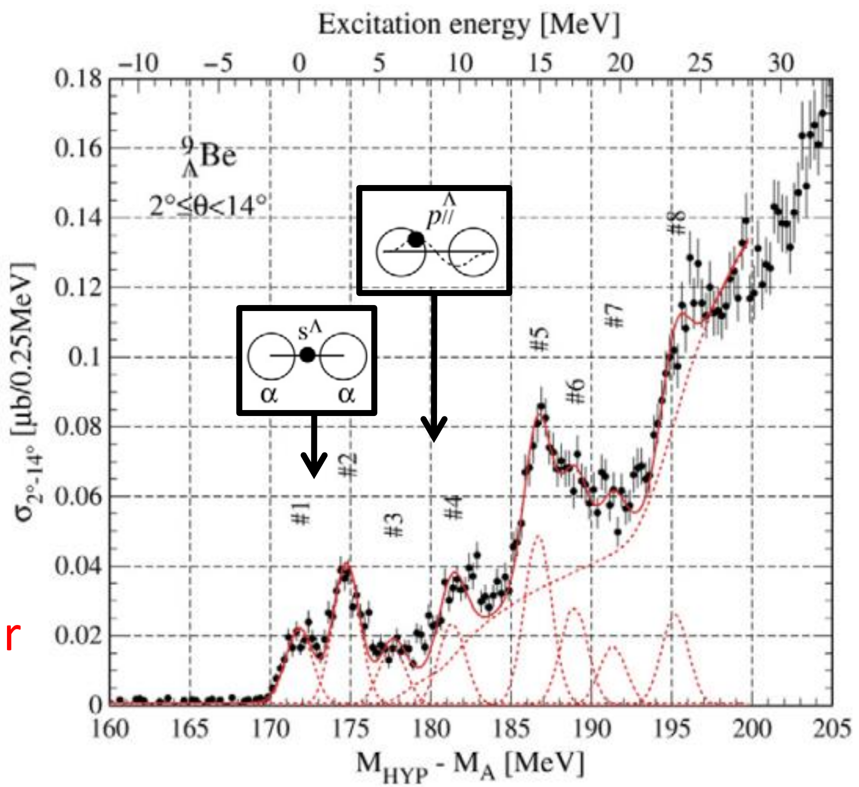
$^{9}_{\Lambda}$Be: axially symmetric 2α clustering

Two bands will be generated as *p*-states [1,2]

- **Anisotropic *p* orbit of Λ hyperon**
- **Axial symmetry of 2α clustering**

→ ***p*-orbit parallel to/perpendicular to the 2α clustering**



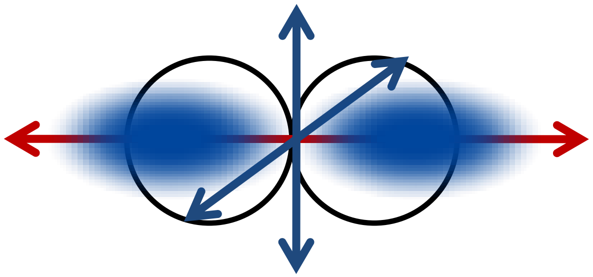


[1] R.H. Dalitz, A. Gal, PRL **36** (1976) 362.
[2] H. Bando, et al., PTP **66** (1981) 2118.;
H. Bando, et al., IJMP **21** (1990) 4021.
[3] O. Hashimoto et al., NPA **639** (1998) 93c.

Split of p-state in ${}^{9}_{\Lambda}$Be

◆ ${}^{9}_{\Lambda}$Be with 2α cluster structure

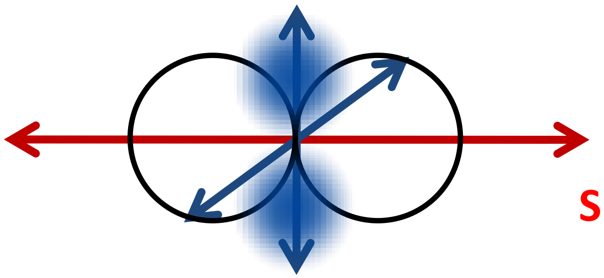
<u>*p* orbit parallel to 2α (long axis)</u>



Large overlap

Deeply bound

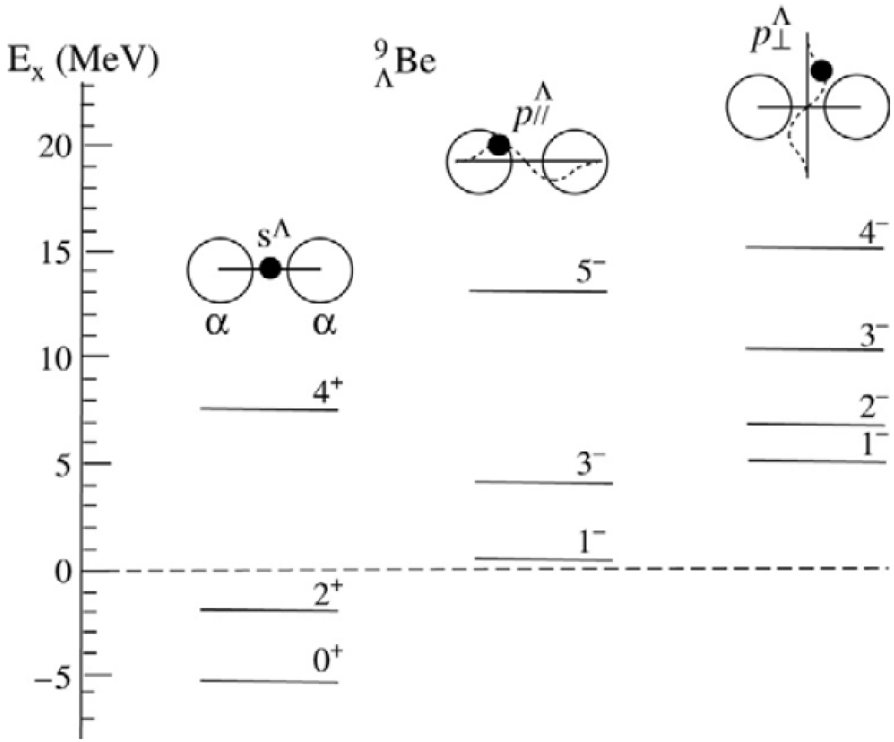
<u>*p* orbit perpendicular to 2α (short axes)</u>



Small overlap

Shallowly bound

Split corresponding to long/short axes



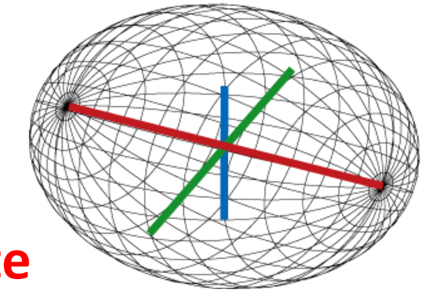
[1] R.H. Dalitz, A. Gal, PRL **36** (1976) 362.
[2] H. Bando, et al., PTP **66** (1981) 2118.;
H. Bando, et al., IJMP **21** (1990) 4021.

p-states splits into 2 bands depending on the direction of p-orbits

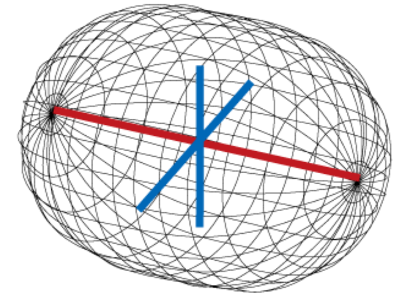
Triaxial deformation

If ^{26}Mg is triaxially deformed nuclei

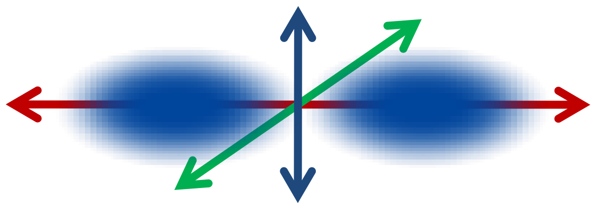
→ *p*-states split into 3 different state



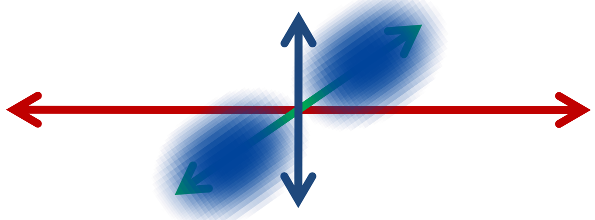
Triaxial deformation



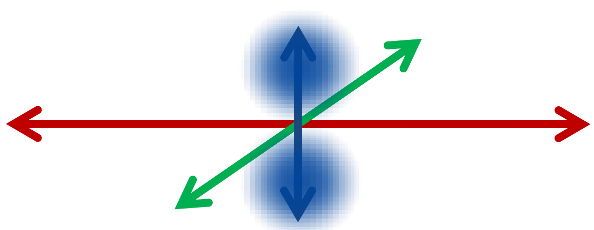
Prolate deformation



Large overlap leads to deep binding



Middle

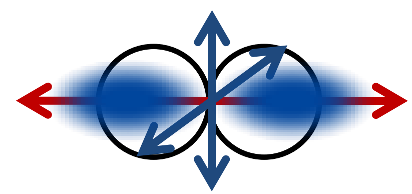


Small overlap leads to shallow binding

cf. prolate deformation

Ex.) $^{9}_{\Lambda}$Be

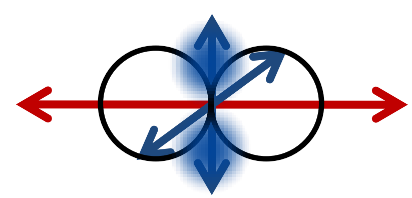
***p* orbit parallel to 2α (long axis)**



Large overlap

Deeply bound

***p* orbit perpendicular to 2α (short axes)**



Small overlap

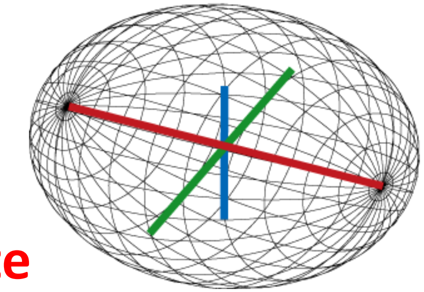
Shallowly bound

Split corresponding to long/short axes

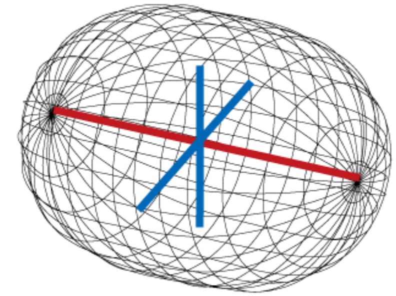
Triaxial deformation

If ^{26}Mg is triaxially deformed nuclei

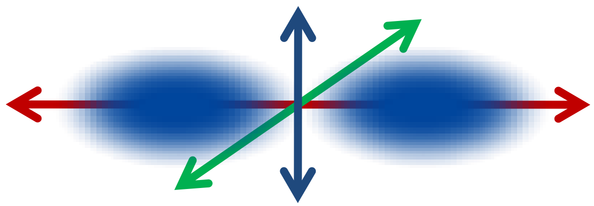
→ *p*-states split into 3 different state



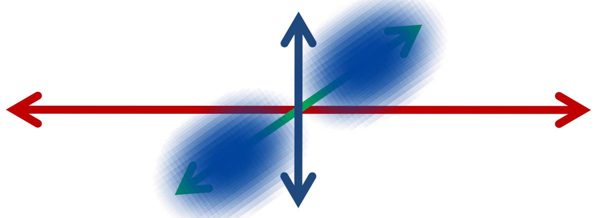
Triaxial deformation



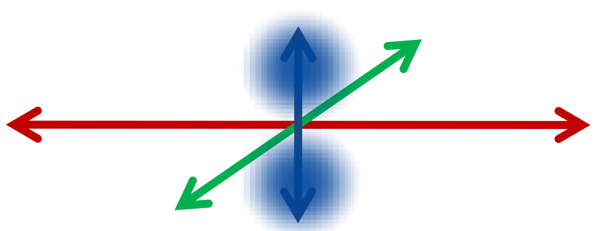
Prolate deformation



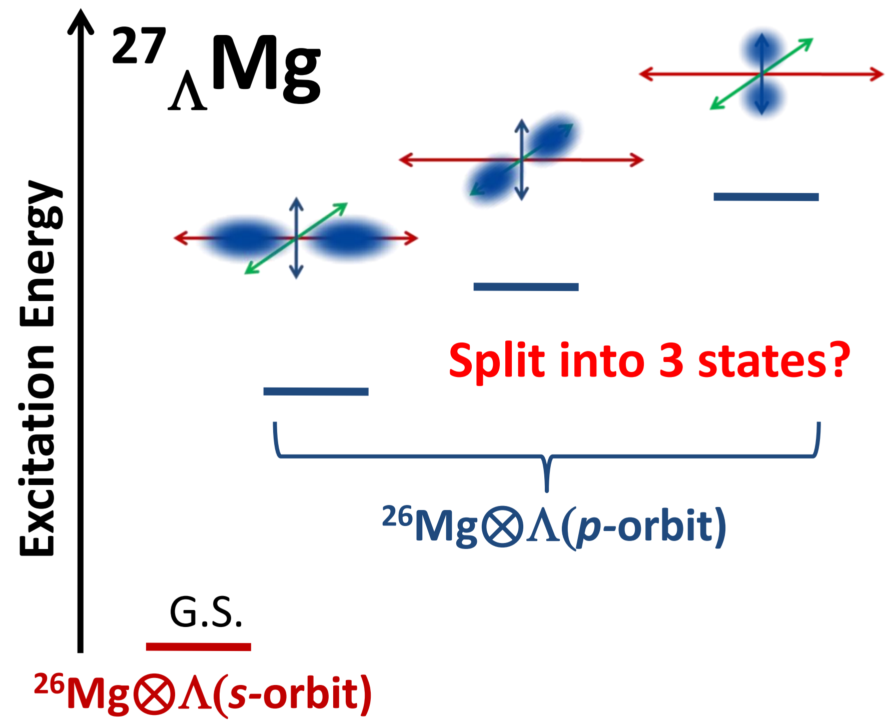
Large overlap leads to deep binding



Middle



Small overlap leads to shallow binding



Observing the 3 different *p*-states is strong evidence of triaxial deformation

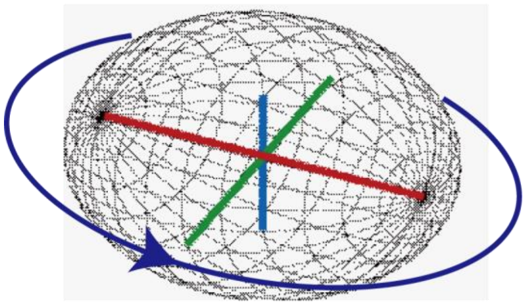
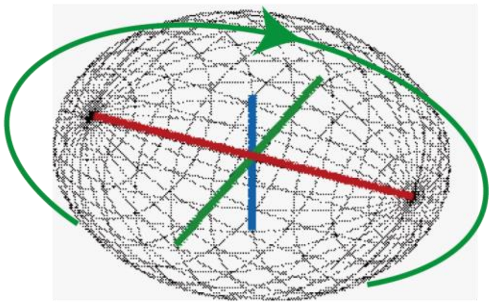
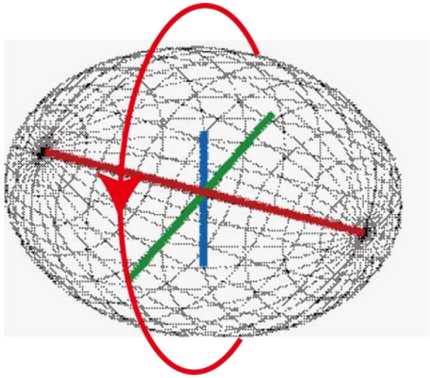
Our (first) task: To predict the level structure of the *p*-states in $^{27}{}_{\Lambda}$Mg

Purpose

◆ Purpose and problem

- To reveal **triaxial deformation of ^{26}Mg**, we will predict the level structure of the **p states** in $^{27}{}_{\Lambda}$Mg

- $^{27}{}_{\Lambda}\mathrm{Mg}$
  – *p*-states will split into **3 different states**, if ^{26}Mg is triaxially deformed

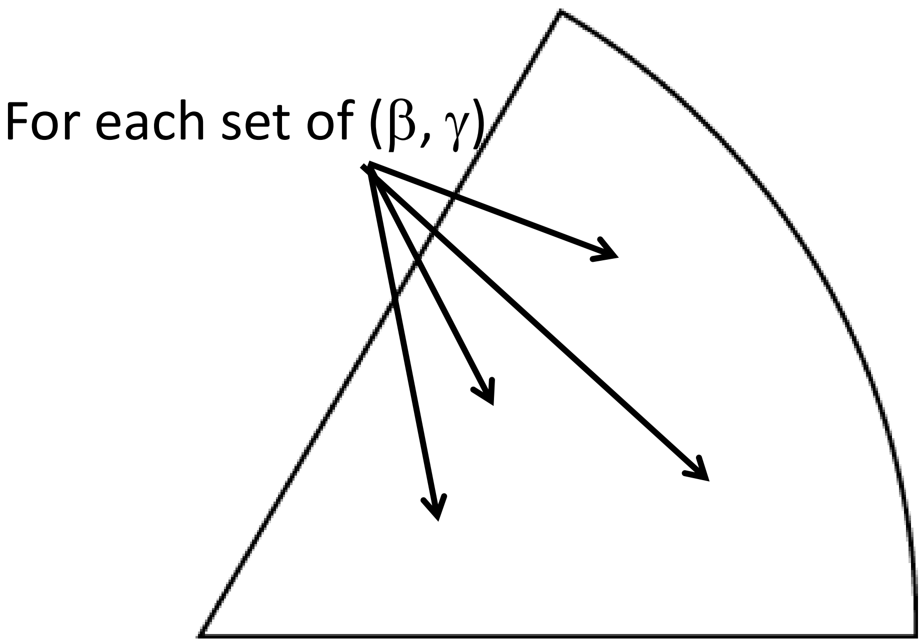
Actual calculation of HyperAMD

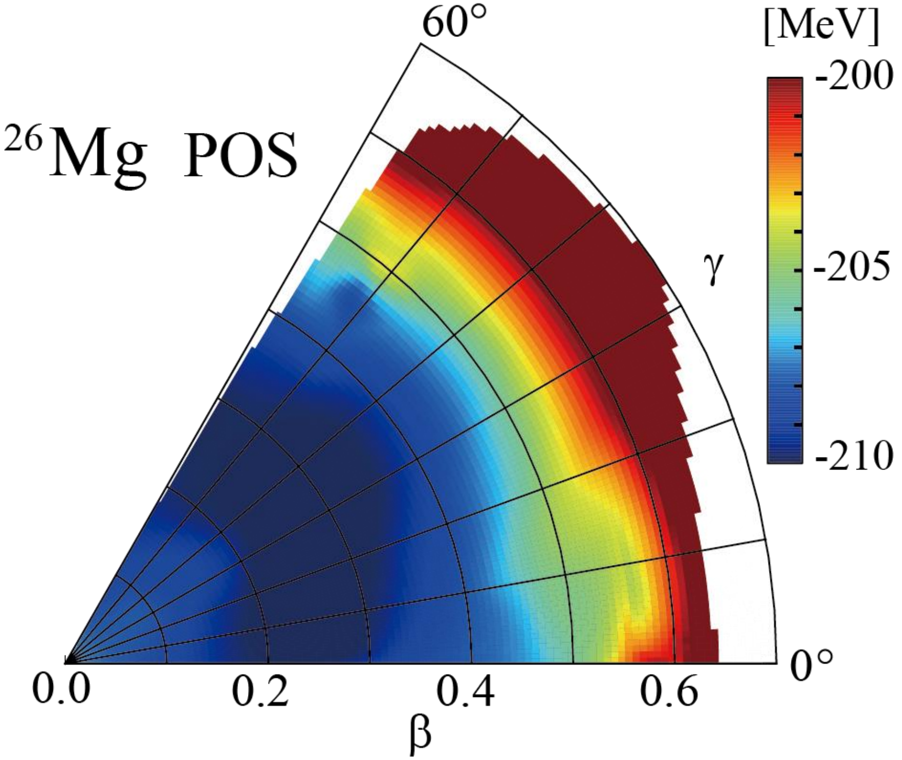
M.Isaka, *et al.*, PRC**83**(2011) 044323
M. Isaka, *et al.*, PRC**83**(2011) 054304

Energy variation with constraints on (β, γ)

- **Energy variation at each set of (β, γ) with parity projection**

⟶ Energy surface on (β, γ) plane

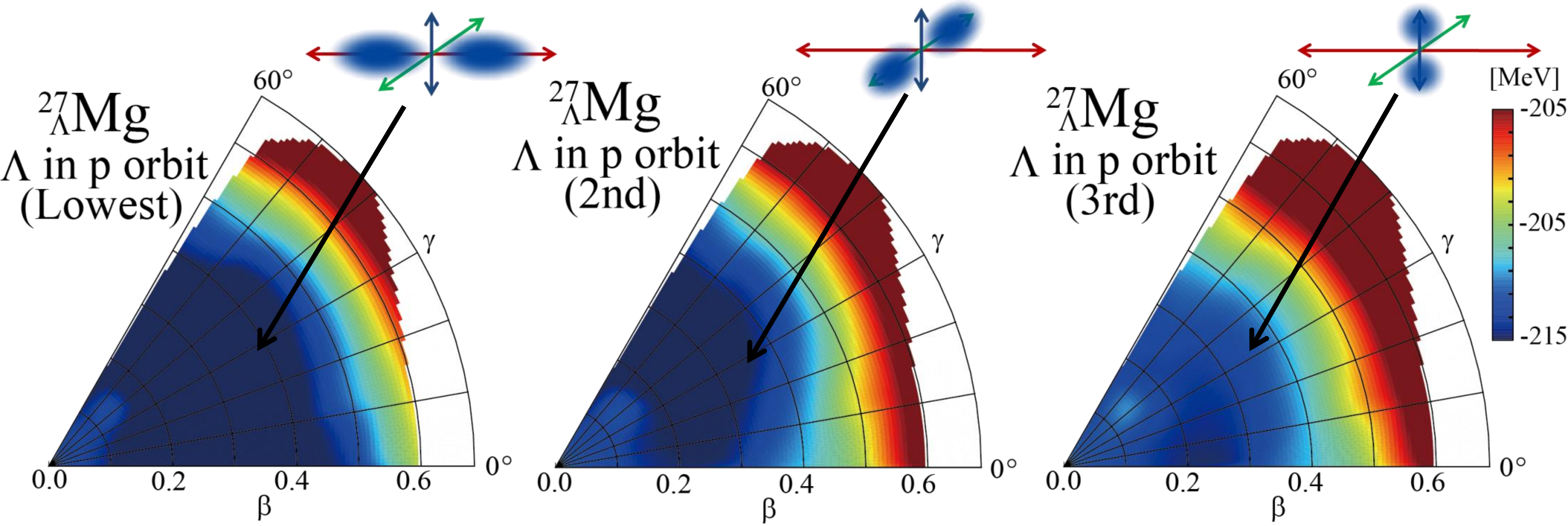




- **In $^{27}{}_{\Lambda}$Mg, we also impose constraint potential on Λ s.p. orbit to calculate Λ in p-states:** $V_f = \lambda \sum_f |\varphi_f\rangle\langle\varphi_f|$

Energy surface on (β, γ) plane

- **“*p*-states” of $^{27}{}_{\Lambda}$Mg: Λ particle in *p* orbit**
  - **3 kinds of *p* states appear by the energy variation with constraints**
  - **With different spatial distribution of Λ (in $\gamma \simeq 30$ deg. region)**



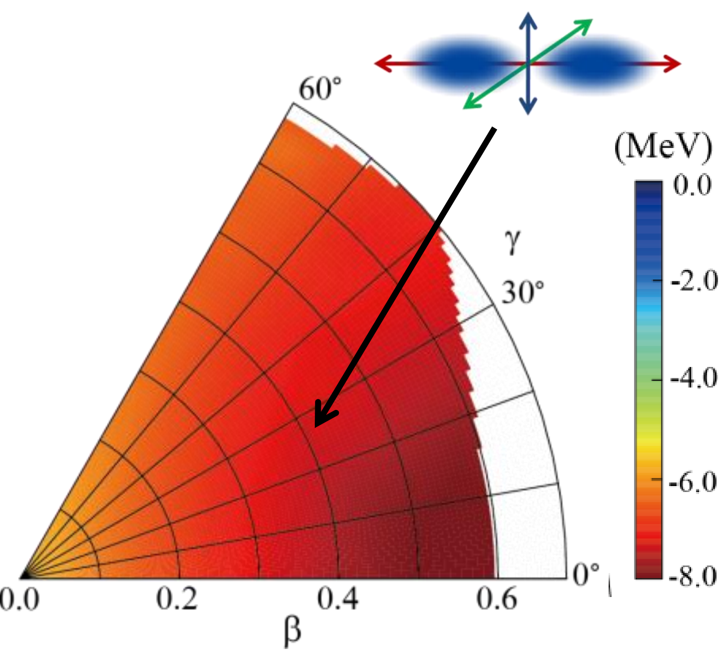
Results： Single particle energy of Λ hyperon

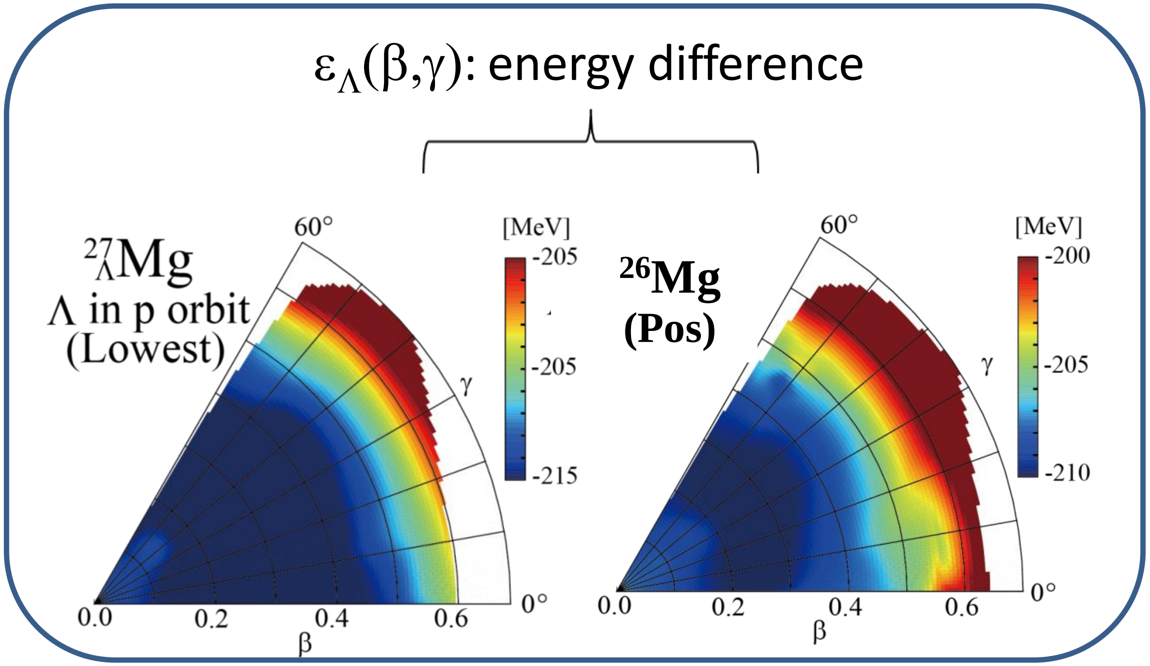
◆ **Λ single particle energy on (β, γ) plane**

$$\varepsilon_{\Lambda}(\beta,\gamma) = E_{\Lambda p}(\beta,\gamma) - E_{core}(\beta,\gamma)$$

$^{27}_{\Lambda}$Mg (AMD, Λ in *p* orbit)

Lowest p state





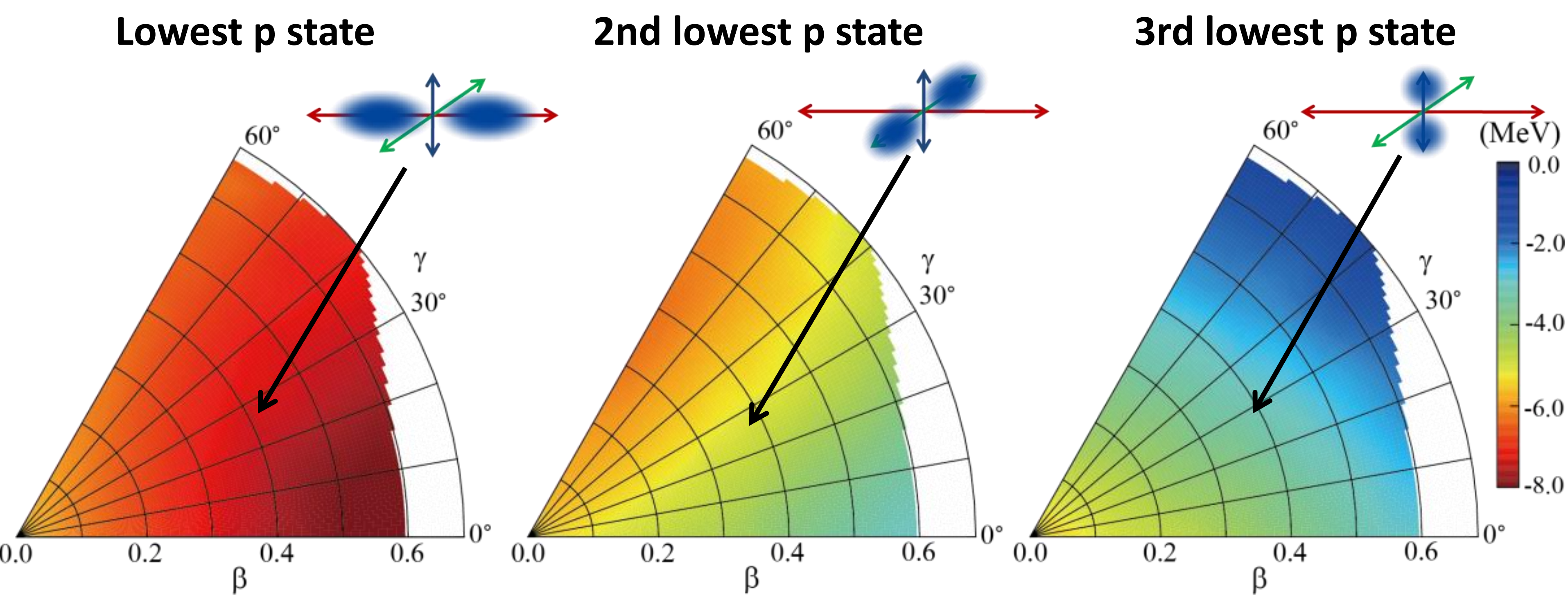
- **Single particle energy of Λ particle is different from each p state**
  - **This is due to the difference of overlap between Λ and nucleons**

Results： Single particle energy of Λ hyperon

◆ **Λ single particle energy on (β, γ) plane**

$$\varepsilon_{\Lambda}(\beta,\gamma) = E_{\Lambda p}(\beta,\gamma) - E_{core}(\beta,\gamma)$$

$^{27}_{\Lambda}$Mg (AMD, Λ in *p* orbit)

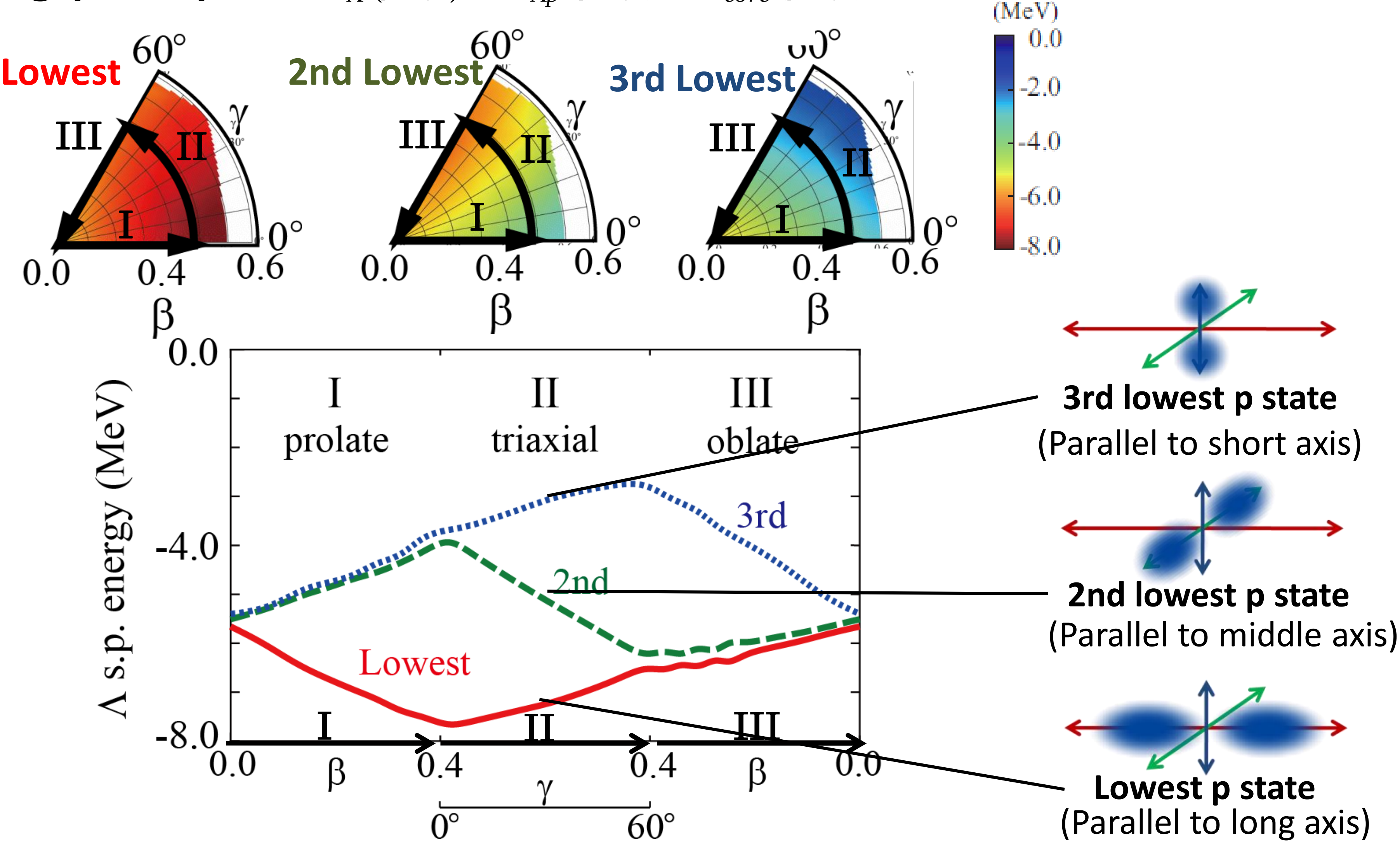


- **Single particle energy of Λ particle is different from each p state**
  - **This is due to the difference of overlap between Λ and nucleons**

Results： Single particle energy of Λ hyperon ε_Λ

$^{27}_{\Lambda}$Mg (AMD)

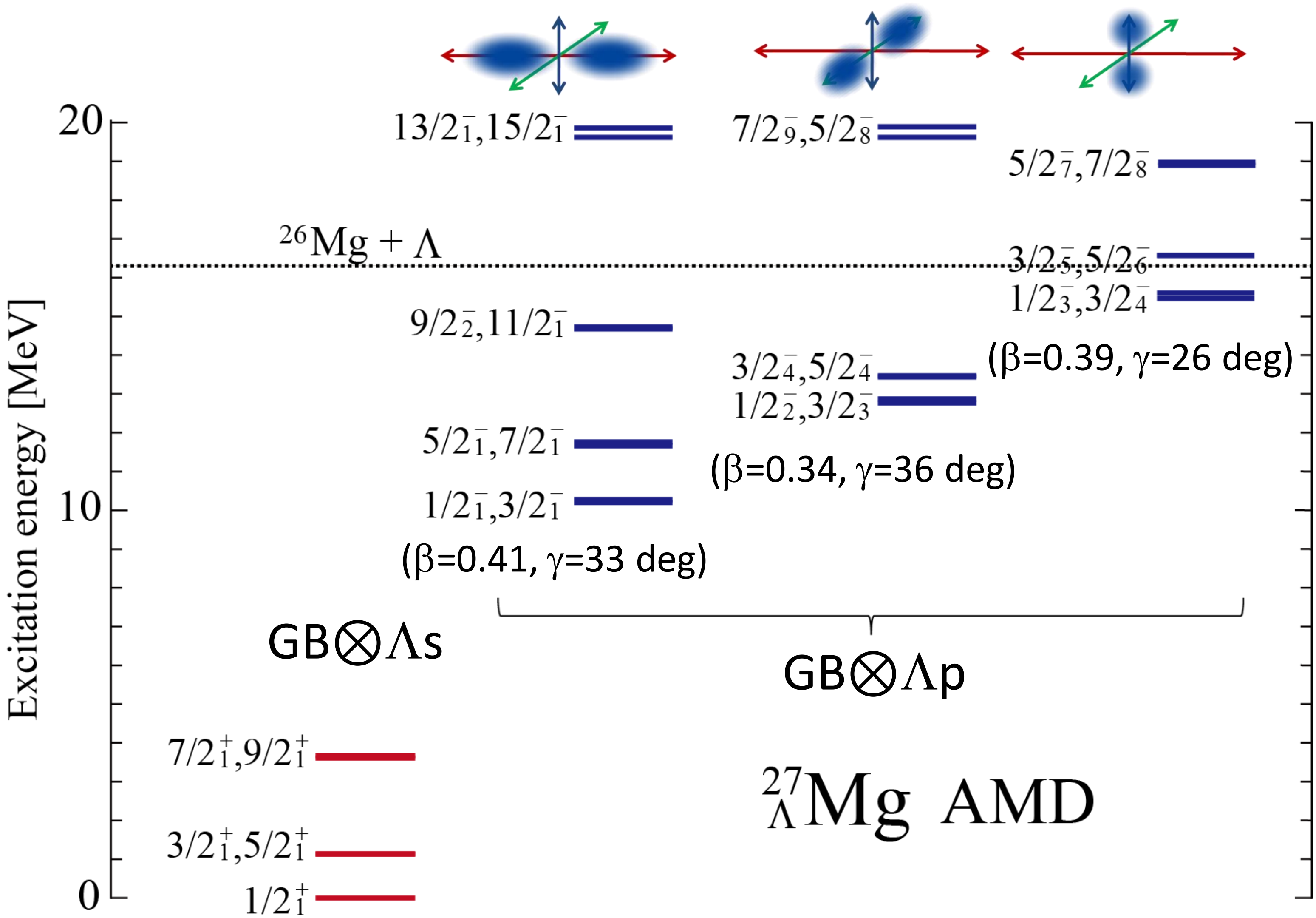
$$\varepsilon_\Lambda(\beta,\gamma) = E_{\Lambda p}(\beta,\gamma) - E_{core}(\beta,\gamma)$$



Λ s. p. energy is different from each other with triaxial deformation

Results: Excitation spectra

- **3 bands are obtained by Λ hyperon in *p*-orbit** → **Splitting of the *p* states**
  - **^{26}Mg⊗Λp(lowest), ^{26}Mg⊗Λp(2nd lowest), ^{26}Mg⊗Λp(3rd lowest)**



Summary

Knowledge of YN interaction will allow us to reveal structure of hypernuclei

- Structure change and modification of nuclear properties by adding a hyperon
- Bounding unbound systems by using hyperons as a glue
- Probing nuclear structure (deformation) by using hyperon

Combination of the modern YN interaction with nuclear models

- Antisymmetrized molecular dynamics + effective YN interaction

Structure changes caused by Λ

- Λ in *p*-orbit enhances the nuclear deformation, while Λ in *s*-orbit reduces it.
- Difference of the Λ binding energy causes the changes of the excitation spectra: Ground state parity of $^{12}{}_{\Lambda}$Be

Probing nuclear deformation by using Λ

- Splitting of the p orbits in $^{27}{}_{\Lambda}$Mg due to triaxial deformation