Modifying and Probing Nuclear Structure using Λ particle

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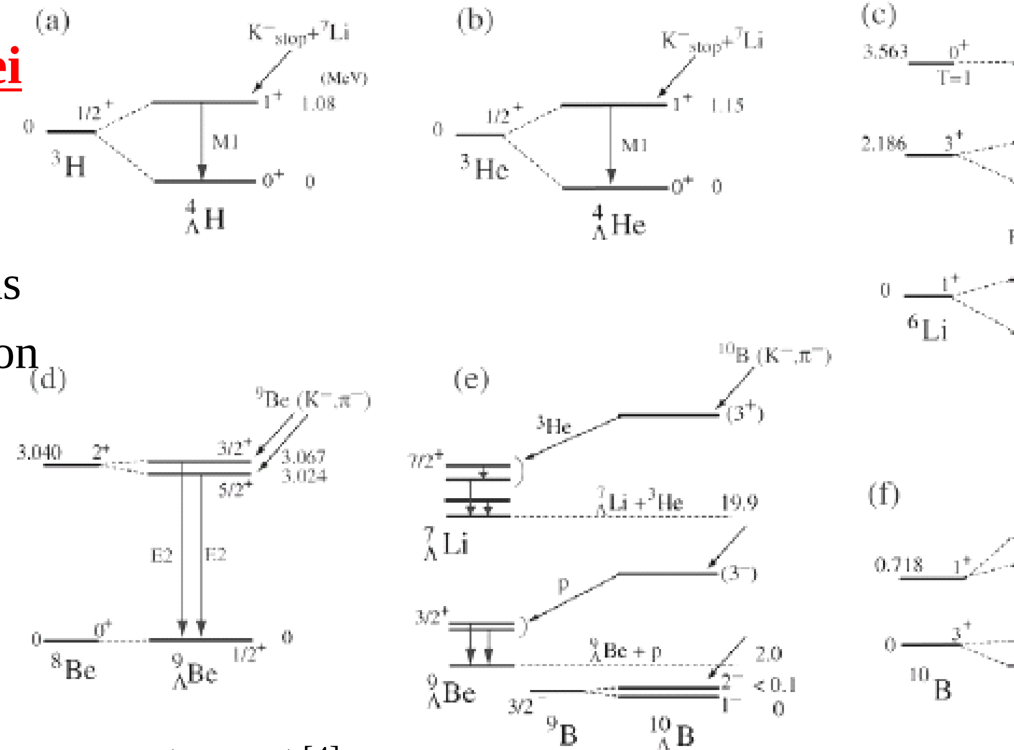
Structure study of Λ hypernuclei



Study of light(*s*, *p*-shell) Λ hypernuclei

Knowledge of YN (YY) interactions

- Interaction models, Lattice QCD
- Exact solution of few-body problems
- Increases of experimental information

Development in nuclear models

- Study of unstable nuclei

  Ex.: Antisymmetrized Molecular Dynamics (AMD)[4]

  - AMD describes dynamical changes of various structure
  - No assumption on clustering and deformation

Combination of modern YN(YY) interactions and nuclear structure models will open new era of hypernuclear study

[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.

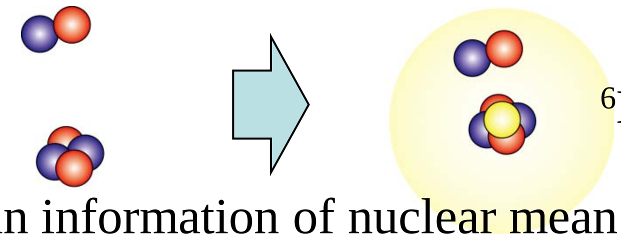
Unique Features of Λ-Hypernuclei

- Y has no Pauli Blocking to N: a unique probe to study nuclear structure
- Y supplies additional attraction to nuclear many body system
- Trace the single Λ particle nature in hypernuclei allows to study the nuclear mean field

For example:

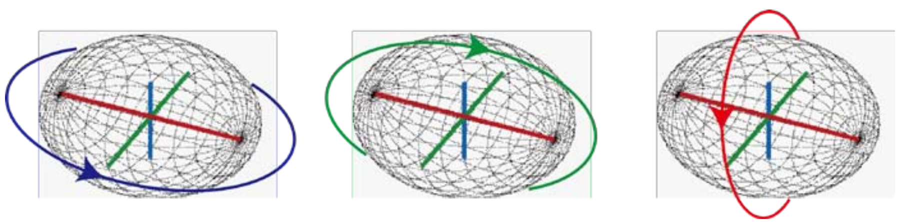
1. Λ will change nuclear structure by its attractive interaction with N
   Modify nuclear properties by Λ

^{6}Li(α+d)

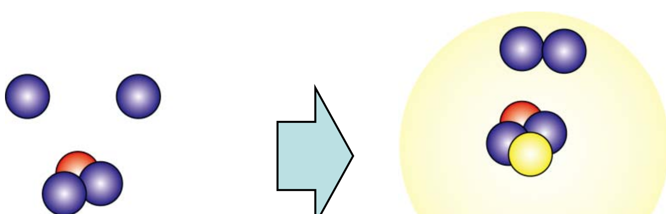


^{6}Li(α+Λ+d)

2. By looking at the motion of the Λ, we'll obtain information of nuclear mean field



3. We can bound an unbound system using Λ



^{5}H(unbound) $^{6}_{\Lambda}$H(bound)

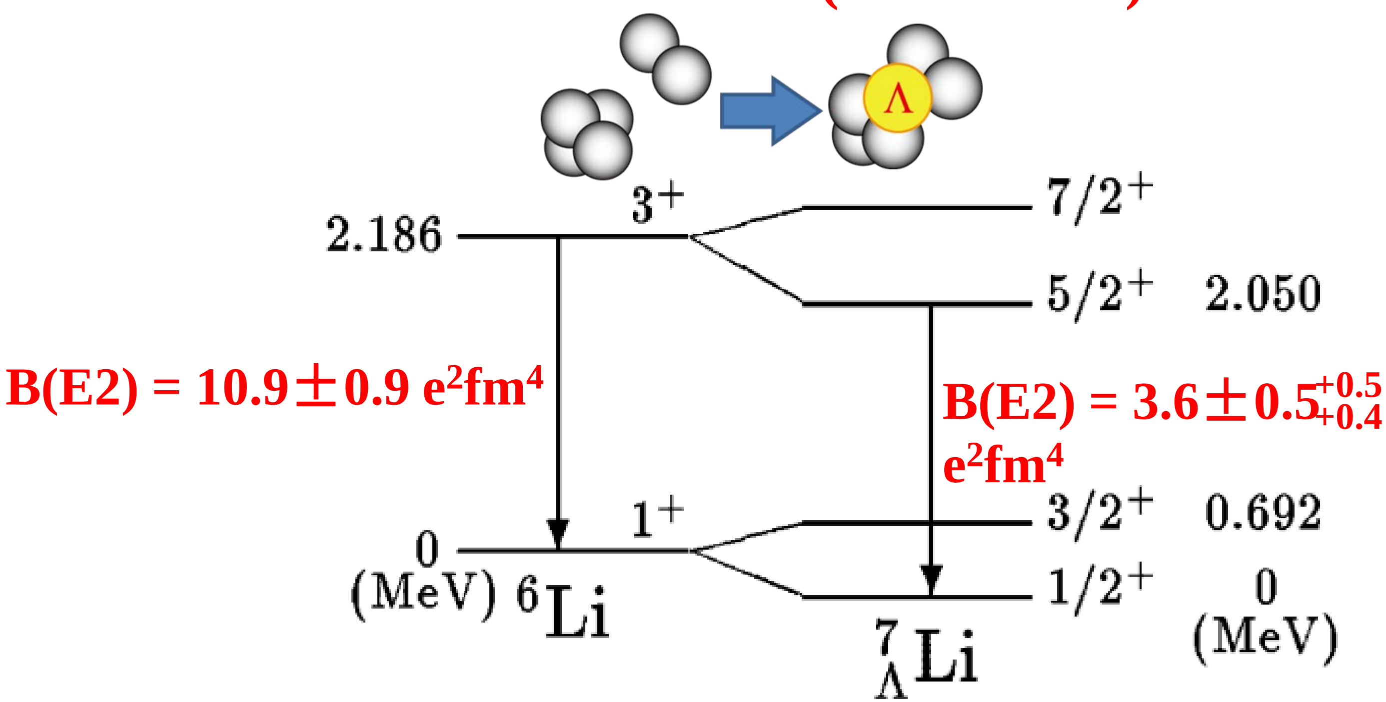
Shrinkage effect: Λ hyperon makes nucleus compact

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

– Li: α + d cluster structure

Λ hyperon penetrates into the nuclear interior

Λ hyperon reduces α + d distance ⟶ **B(E2) reduction (Observable)**



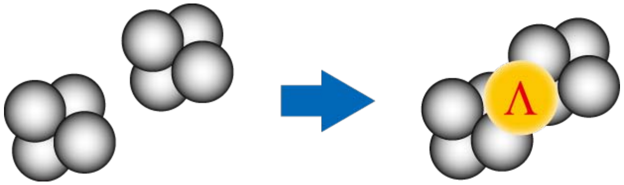
[1] K. Tanida, et al., Phys. Rev. Lett. **86** (2001), 1982. [2]E. Hiyama, et al., Phys. Rev. C59 (1999), 2351.

Structure change by Λ: “Glue-like role”

Glue-like role: Λ hyperon stabilizes unbound state

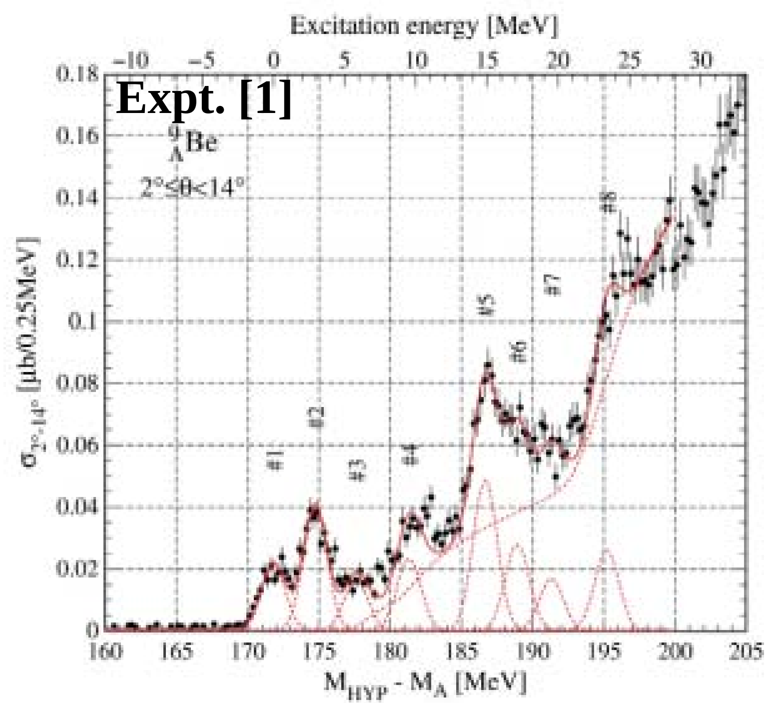
Example: $^{9}_{\Lambda}$Be

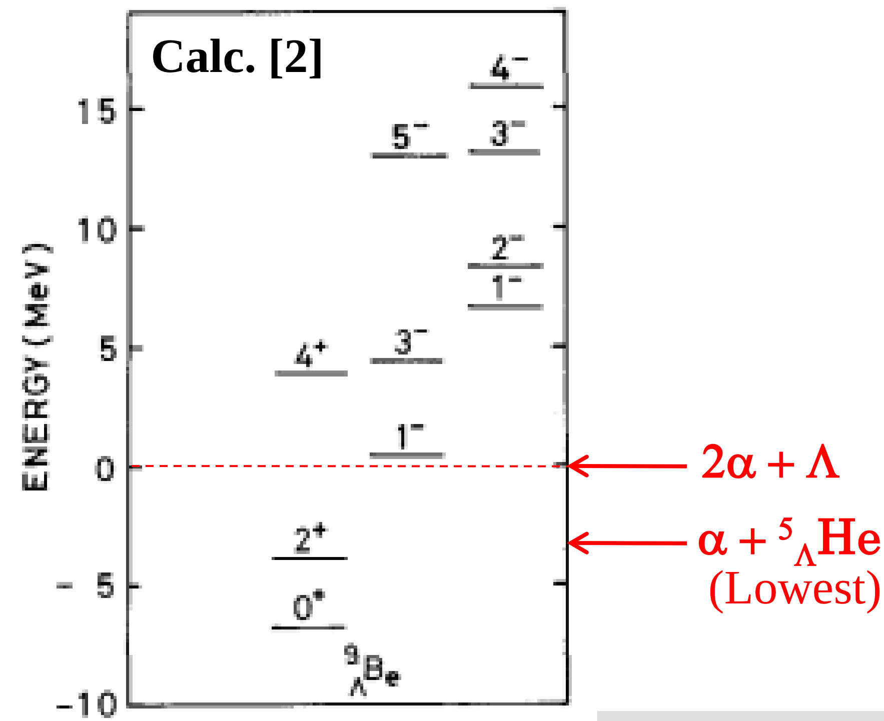
- ^{8}Be is an unstable nucleus
  - Its g.s. lies at about 100 keV above α + α threshold
- $^{9}_{\Lambda}$Be is bound with an α + α + Λ structure



^{8}Be
(unbound)

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



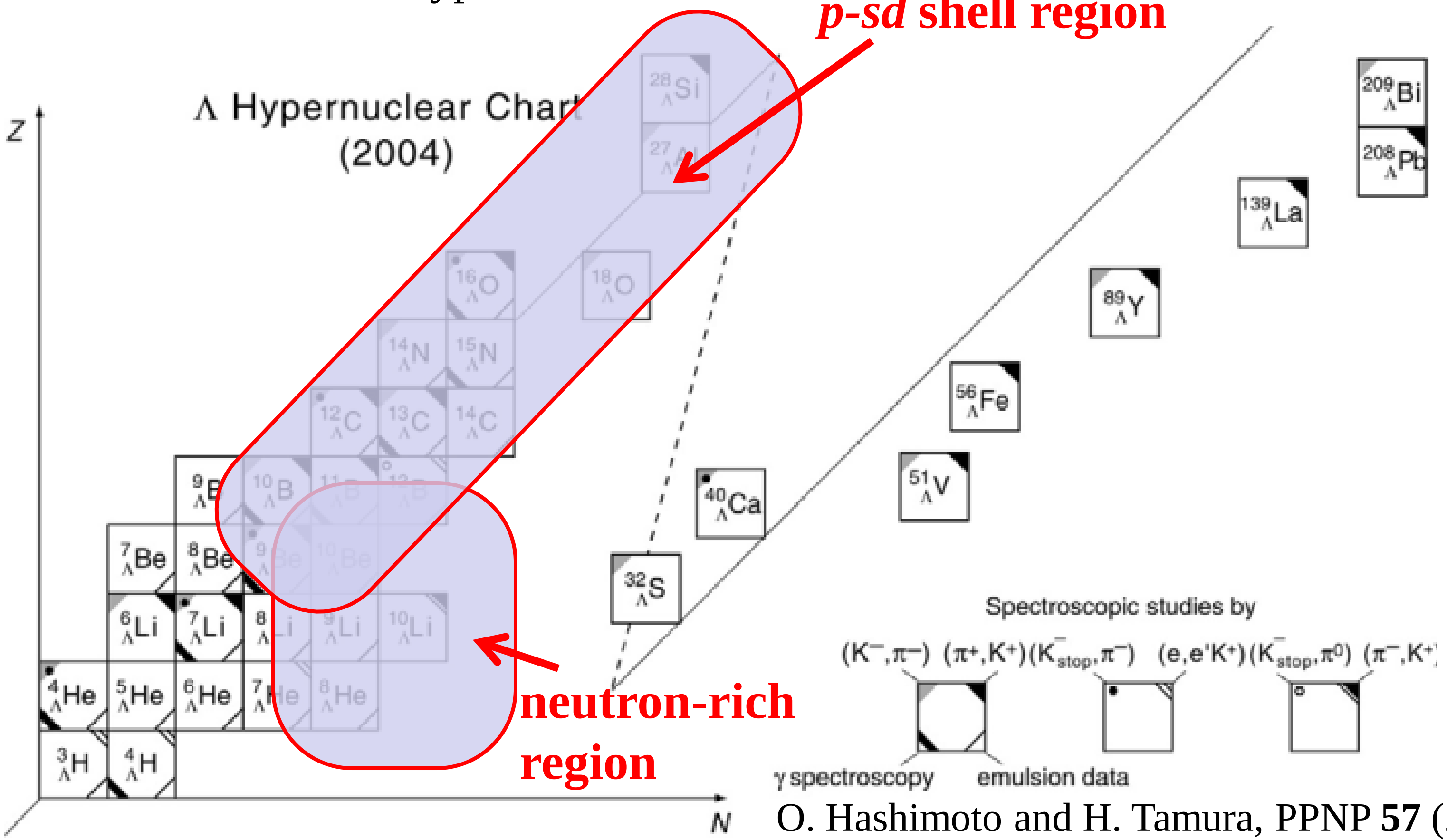


[1] O Hashimoto et. al., Nucl. Phys. A **639** (1998) 93c. [2] Bando et. al., Prog. Theor. Phys. **69** (1983) 913.

Toward heavier and exotic Λ hypernuclei

Experiments at J-PARC, JLab and Mainz

– Various Λ hypernuclei will/can be produced
  - *p*-*sd* shell Λ hypernuclei
  - neutron-rich Λ hypernuclei etc.



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

Full of addictive issues !

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 (Central force) [1]

◆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.：**

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

[1] Y. Yamamoto, T. Motoba, H. Himeno, K. Ikeda and S. Nagata, Prog. Theor. Phys. Suppl. 117 (1994), 361.

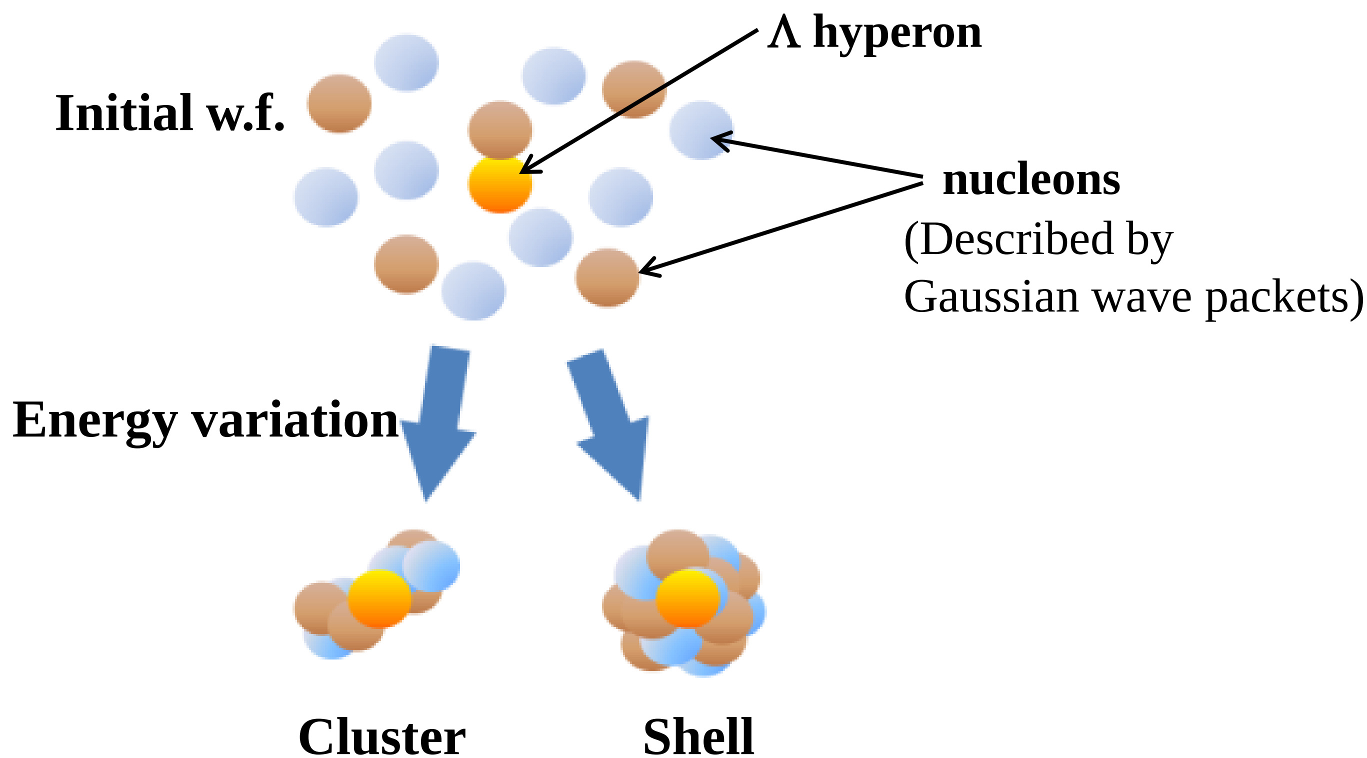
Theoretical framework: HyperAMD

Procedure of the calculation

Variational Calculation

$$\frac{dX_i}{dt} = \frac{\kappa}{\hbar}\frac{\partial H^{\pm}}{\partial X_i^*} \qquad \kappa < 0$$

- Imaginary time development method
- Variational parameters: $X_i = Z_i, z_i, \alpha_i, \beta_i, a_i, b_i, \nu_i, c_i$



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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)

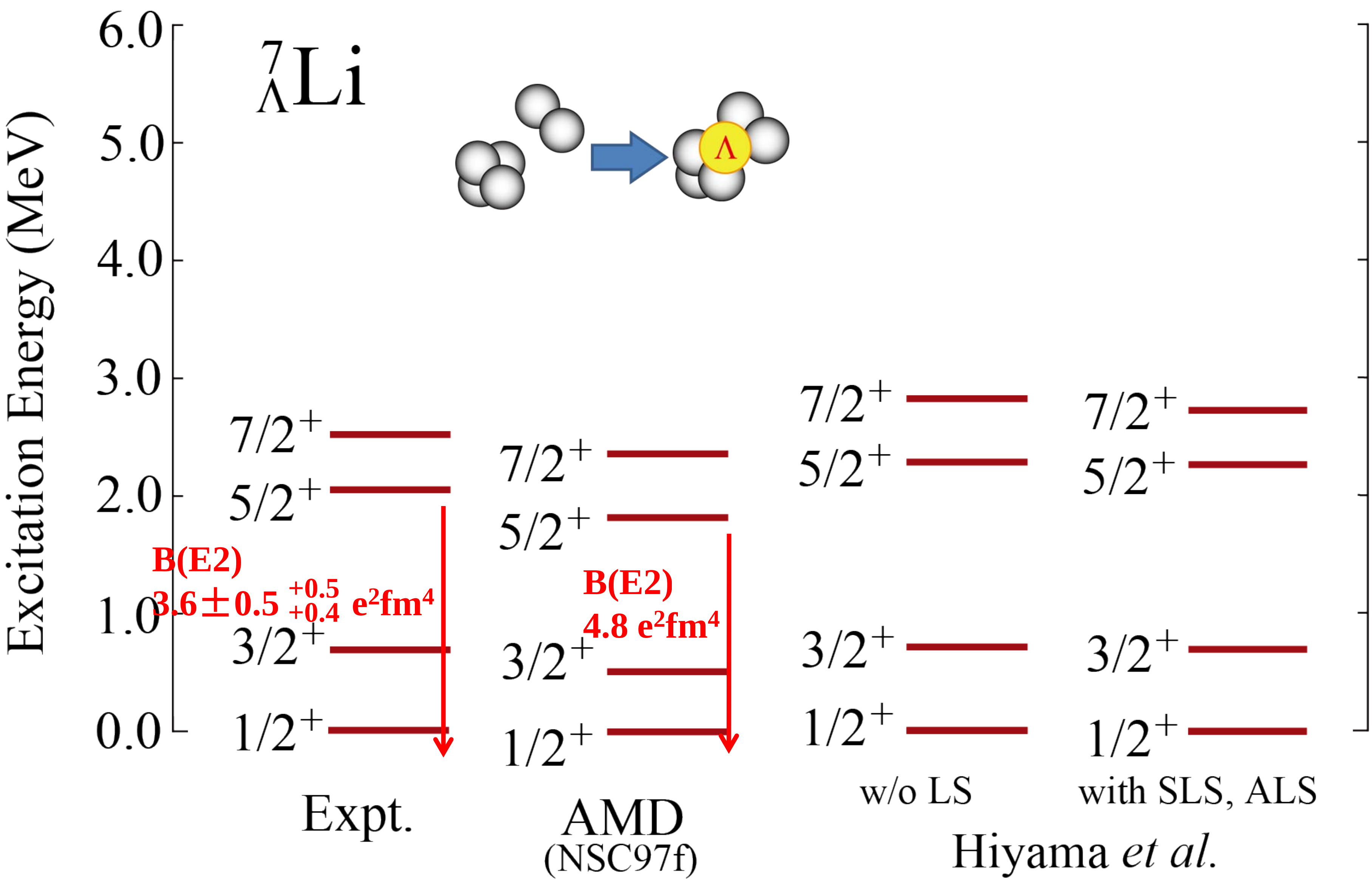
- Superposition of the w.f. with different configuration
- Diagonalization of $H_{sK,s'K'}^{J\pm}$ and $N_{sK,s'K'}^{J\pm}$

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

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

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

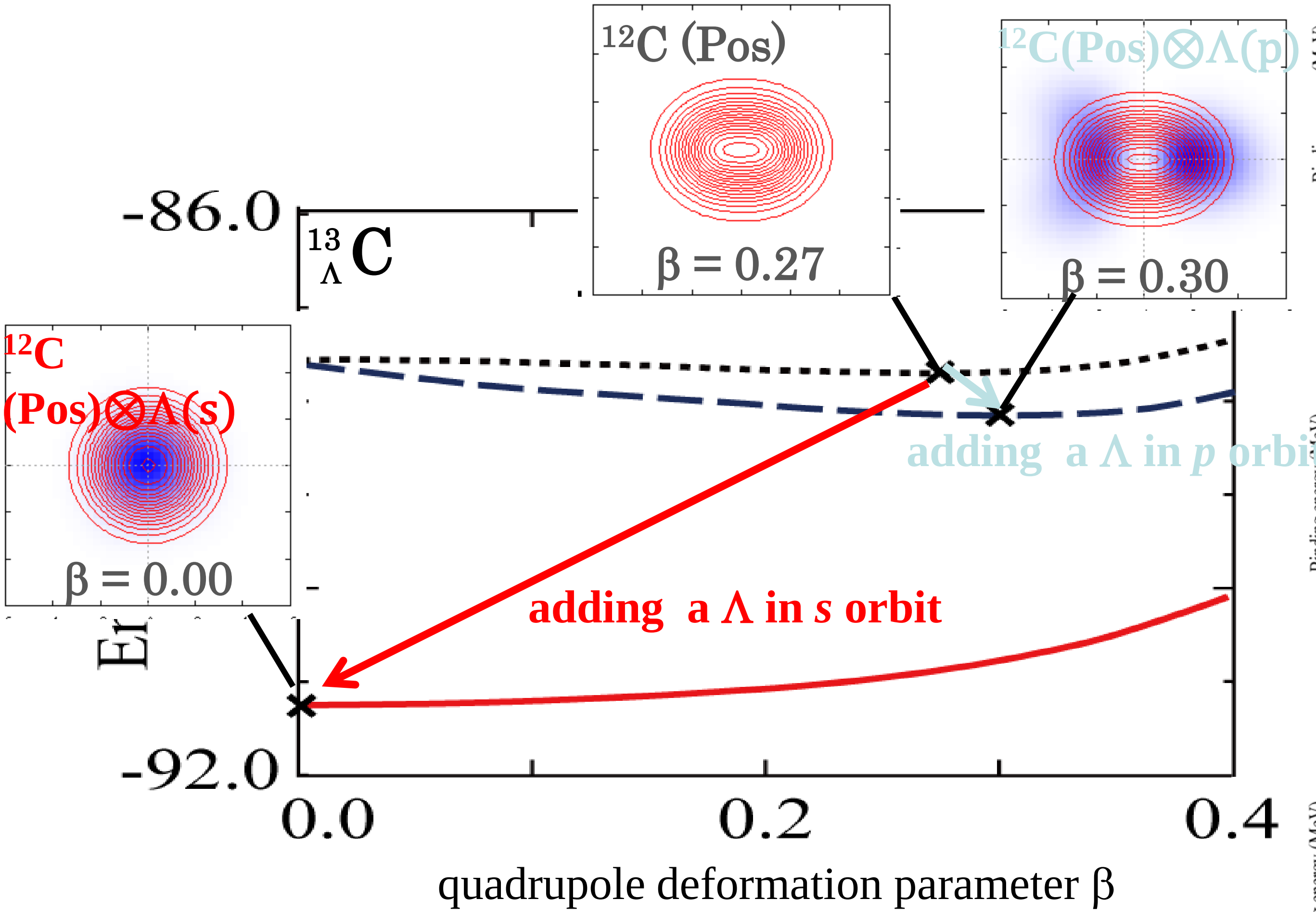
Application of HyperAMD: ${}^{7}_{\Lambda}$Li

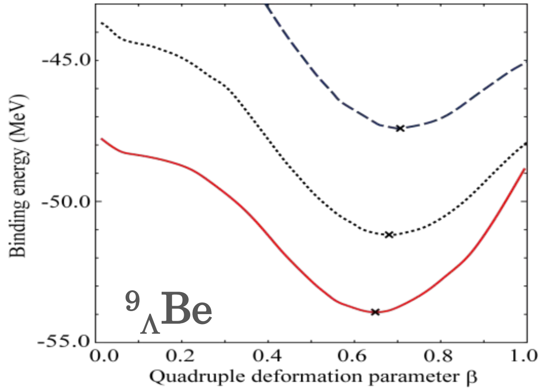


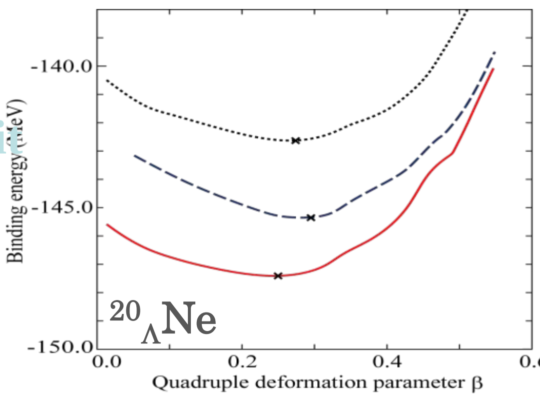
E. Hiyama, et al., PRC **74**, 054312

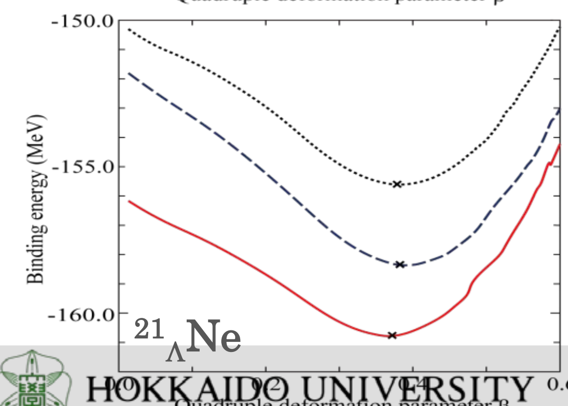
Modifying Nuclear Structure using Λ

How Λ modifies nuclear deformation?







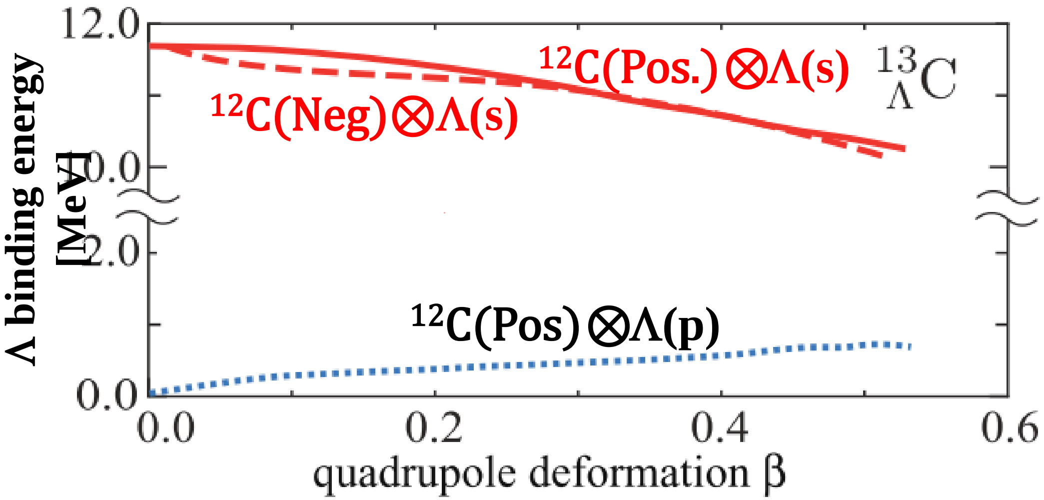


Backup: Reason of deformation change

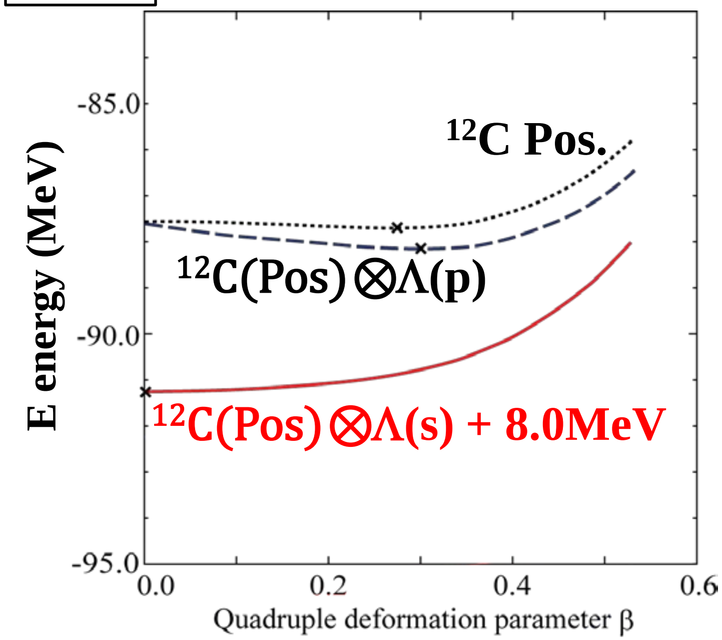
Binding Energy of Λ hyperon

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

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



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



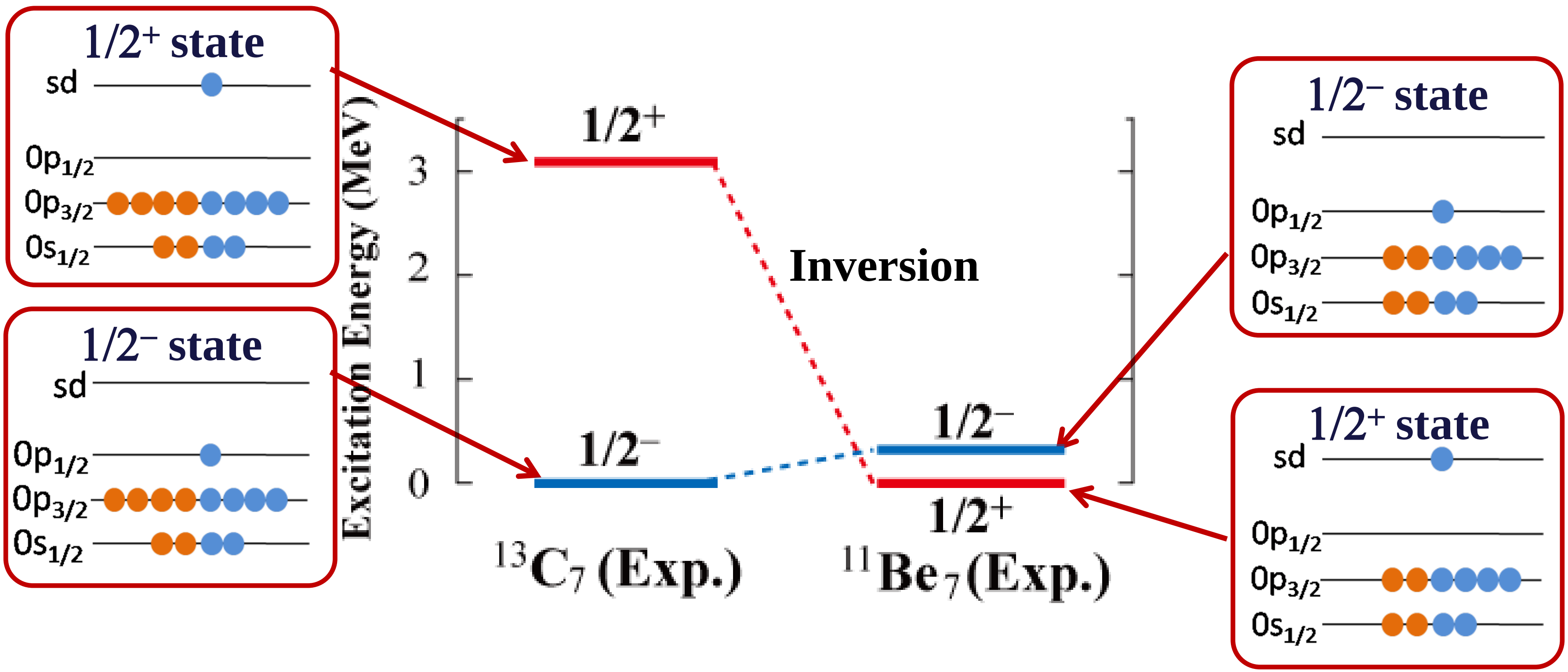
Λ hyperon <u>in *p* orbit</u> enhances the nuclear deformation, while Λ hyperon <u>in *s* orbit</u> reduces it

Modifying Nuclear Structure using Λ

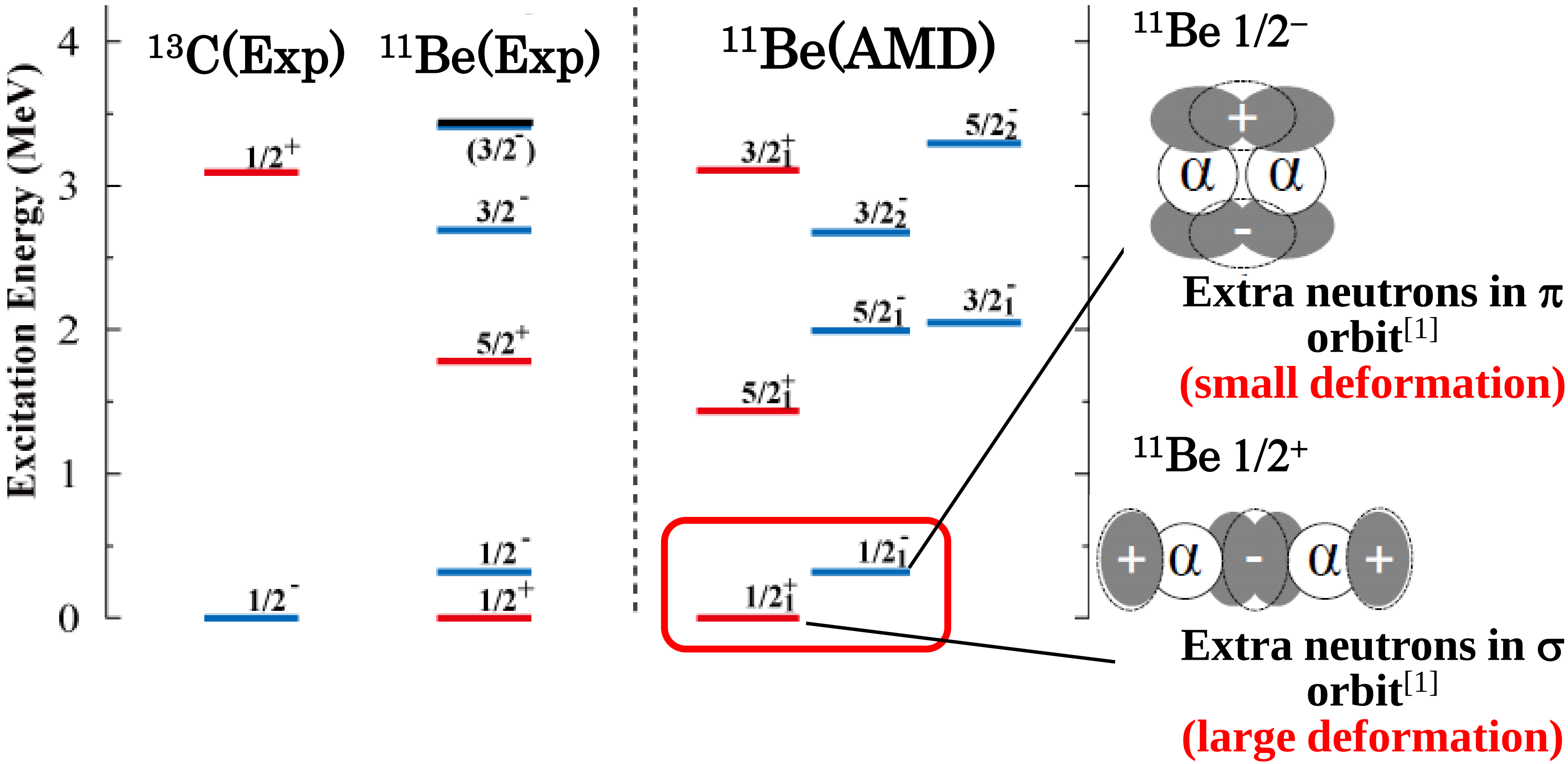
Parity inversion of the ${}^{11}_{4}\mathrm{Be}_7$ ground state

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

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



Excitation spectra of ^{11}Be

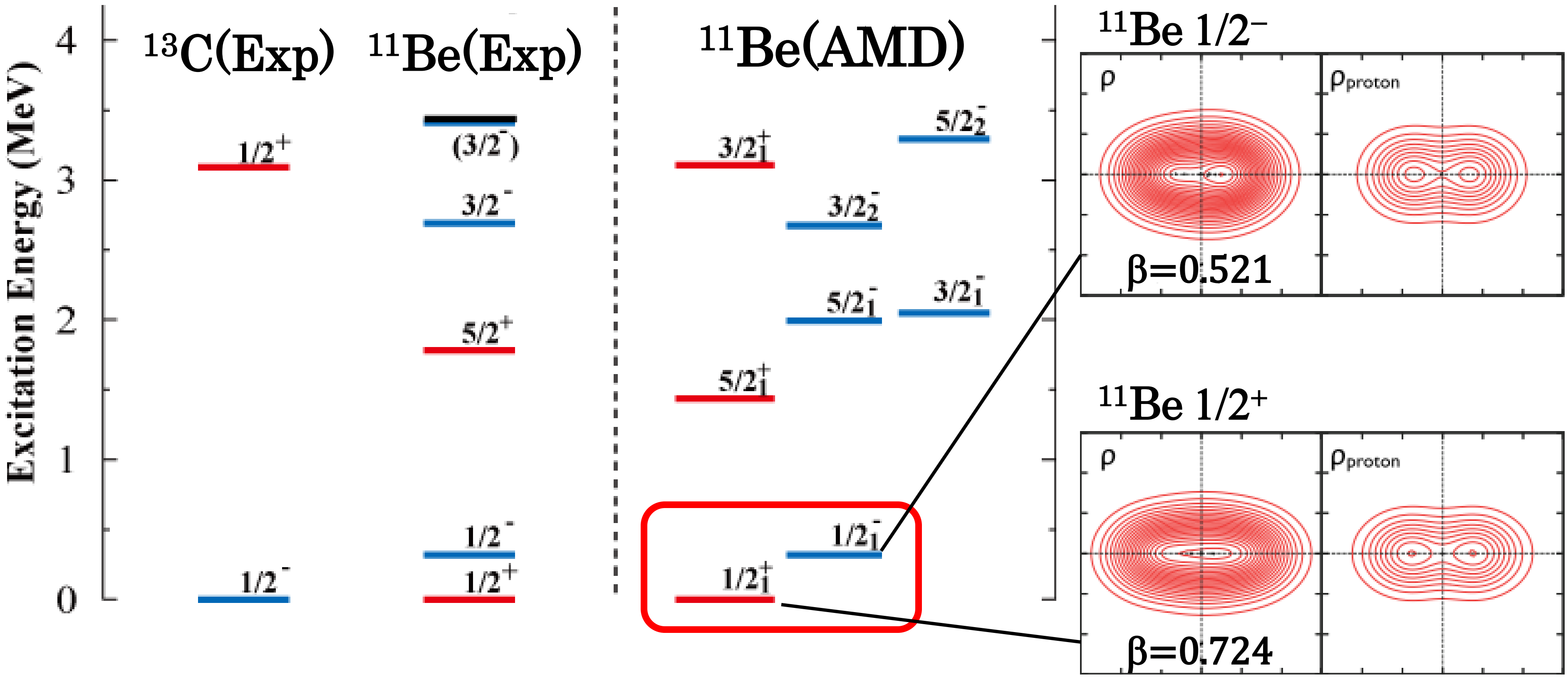


- Deformation of the 1/2⁻ state is smaller than that of the 1/2⁺ state

  → Difference in the orbits of extra neutrons

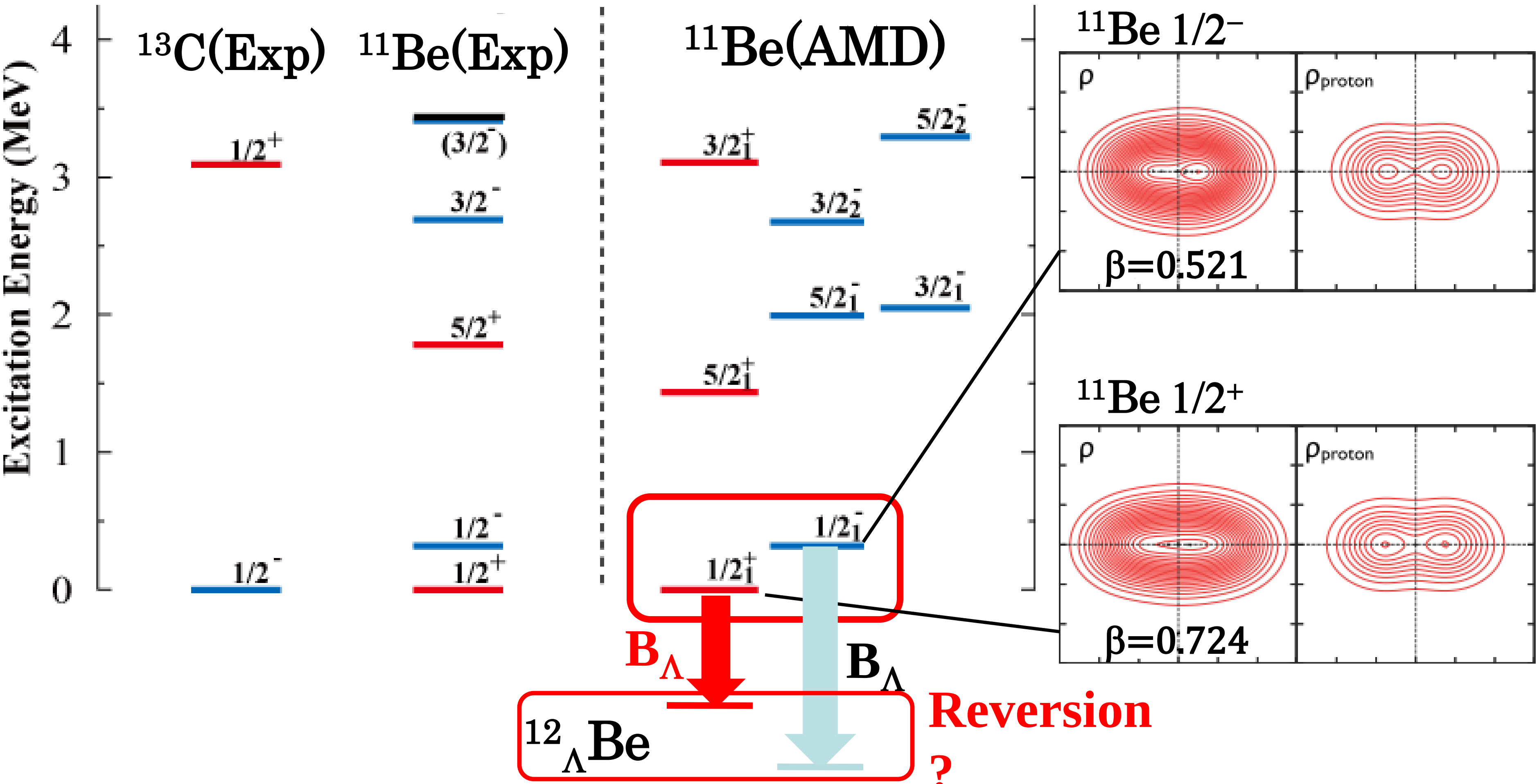
- ^{11}Be has 2α clusters with 3 surrounding neutrons

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



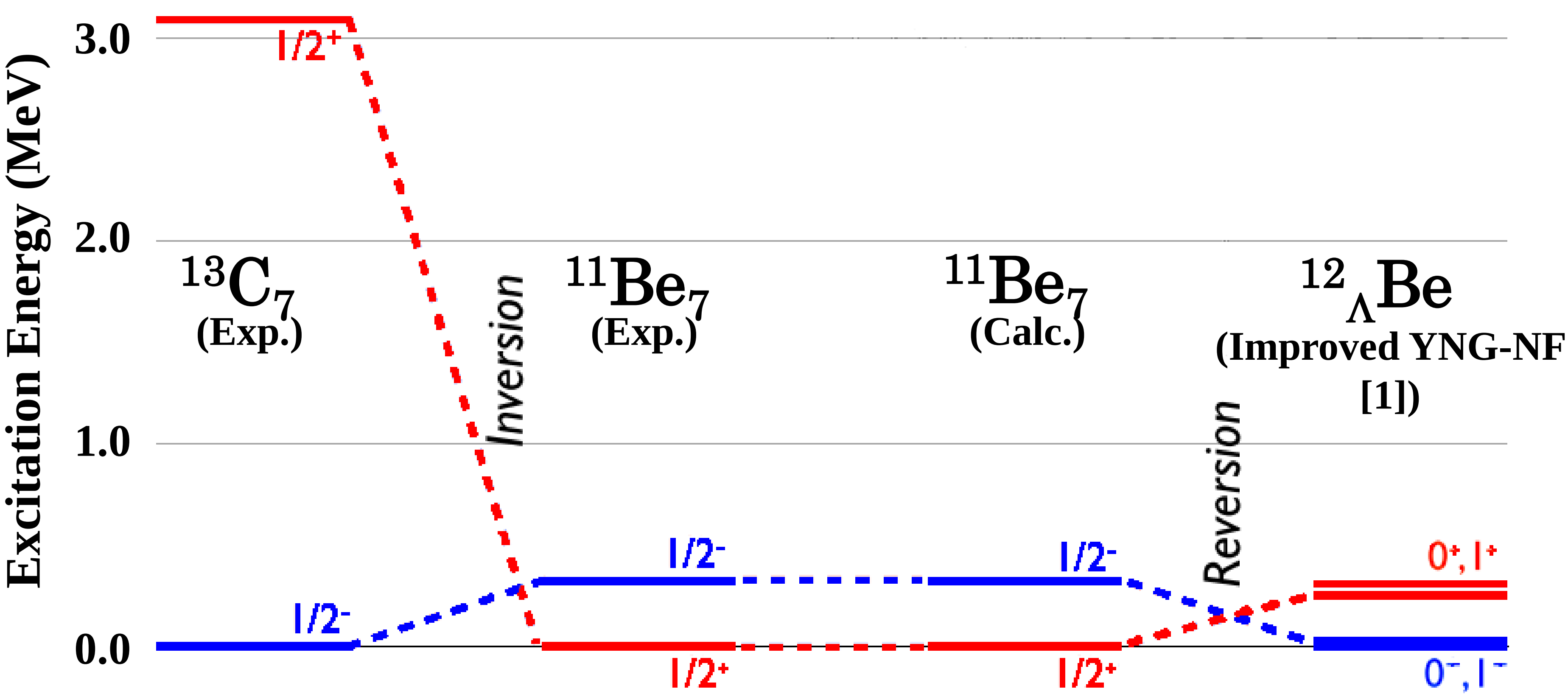
- **Λ hyperon in *s* orbit is deeply bound at smaller deformation**
- **Λ hyperon in *s* orbit is weakly bound at larger deformation**

Parity reversion of the $^{12}_{\Lambda}$Be ground state may occur by Λ in *s* orbit

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

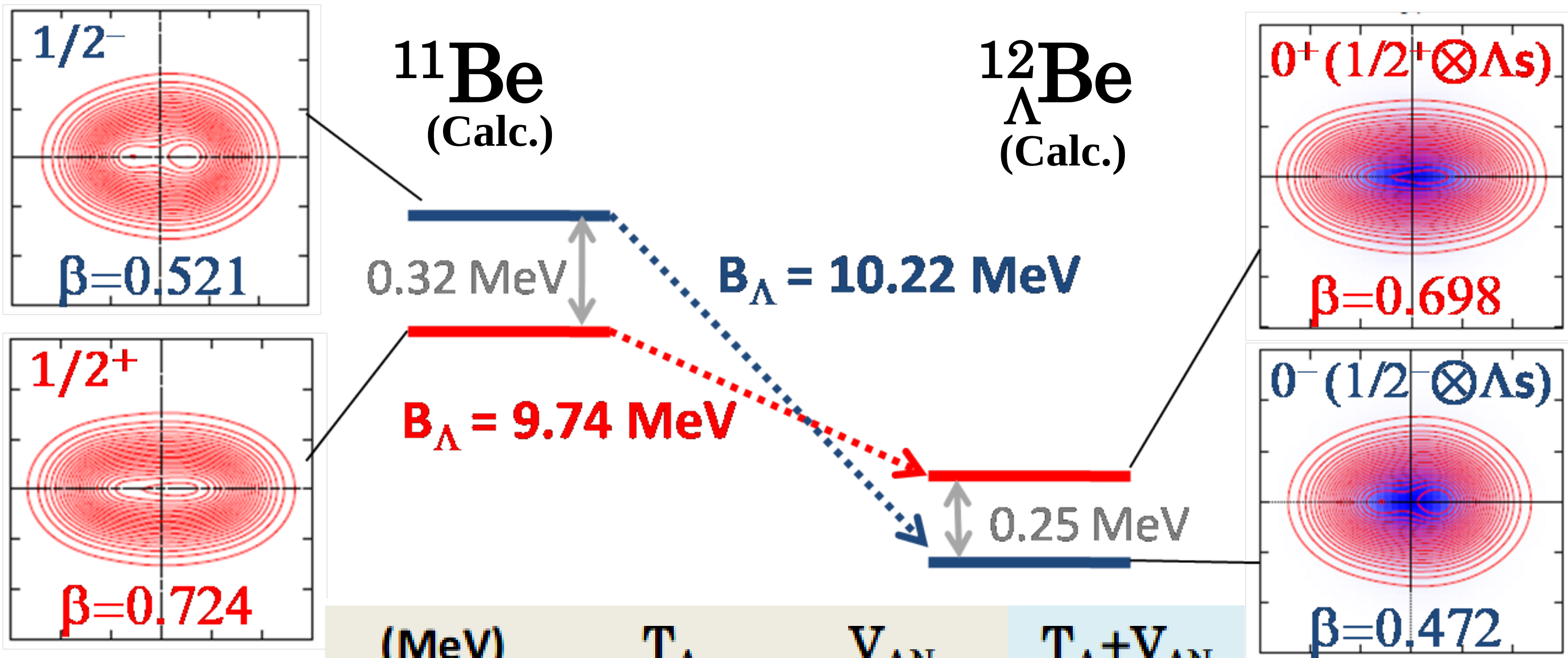
Ground state of $^{12}_{\Lambda}Be$

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



[1] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Prog. Theor. Phys. 97 (1997), 881.

Deformation and Λ binding energy



(MeV)	T_Λ	$V_{\Lambda N}$	$T_\Lambda+V_{\Lambda N}$
0_1^-(GS)	6.71	−16.93	−10.22
0_1^+	6.68	−16.42	−9.74

- Λ hyperon coupled to the $1/2^-$ state is more deeply bound than that coupled to the $1/2^+$ state
  - This is because the deformation of the $1/2^-$ state is smaller than that of the $1/2^+$ state

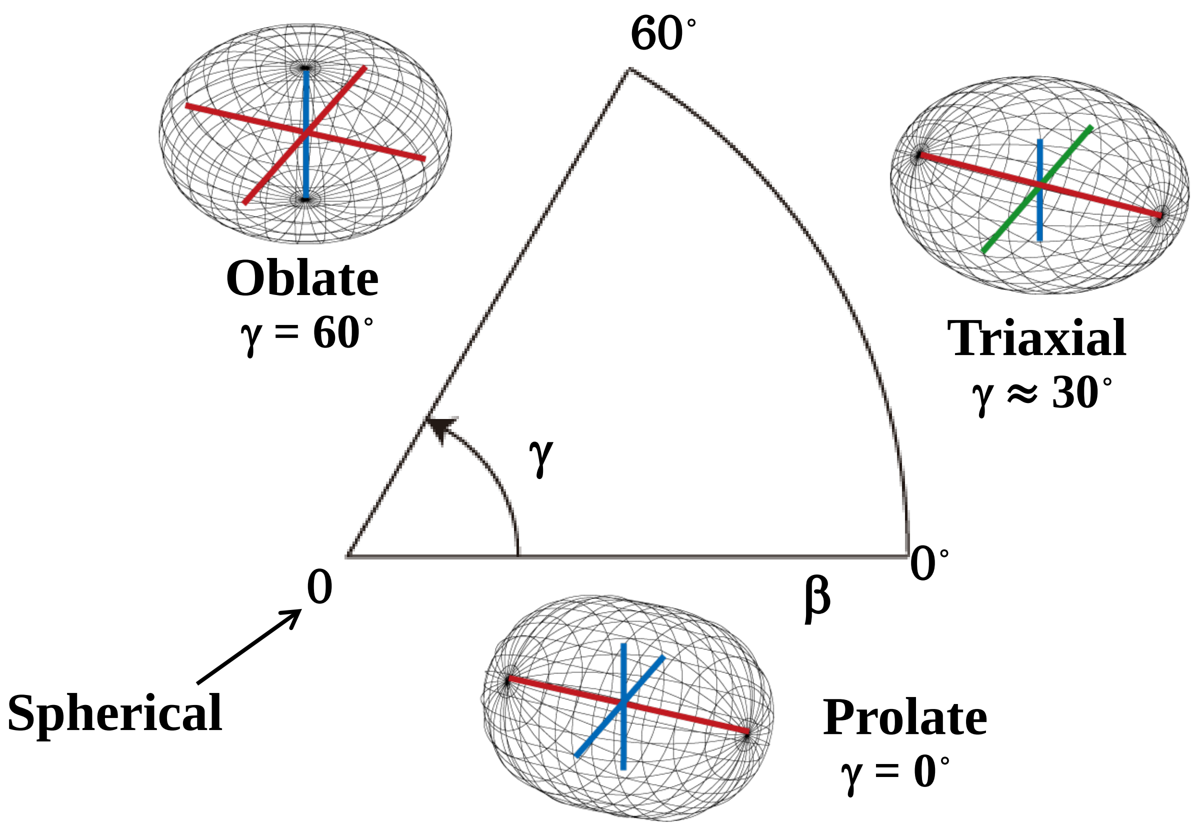
Probing Nuclear Deformation using Λ

Probing Nuclear Deformation using Λ

Many nuclei manifests various quadrupole deformation

(parameterized by quadrupole deformation parameters β and γ)

Most of them are prolate or oblate deformed (axially symmetric)

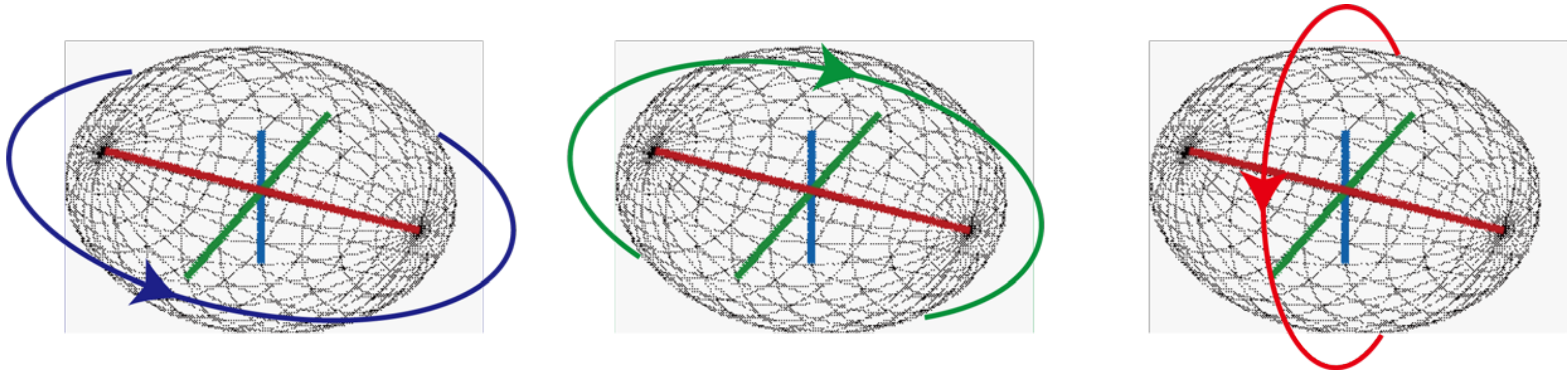


Triaxial deformed nuclei are not many and its identification is not easy.

Probing Nuclear Deformation using Λ

A simple idea …

- Λ is a “distinguish particle” to N (no Pauli exclusion): a unique probe to study nuclear structure
- Trace the single Λ particle nature in heavy hypernuclei allows to study the nuclear mean field
- Energy of p-orbit should split into three depending on the direction of its orbital angular momentum, if the core nucleus is triaxially deformed.

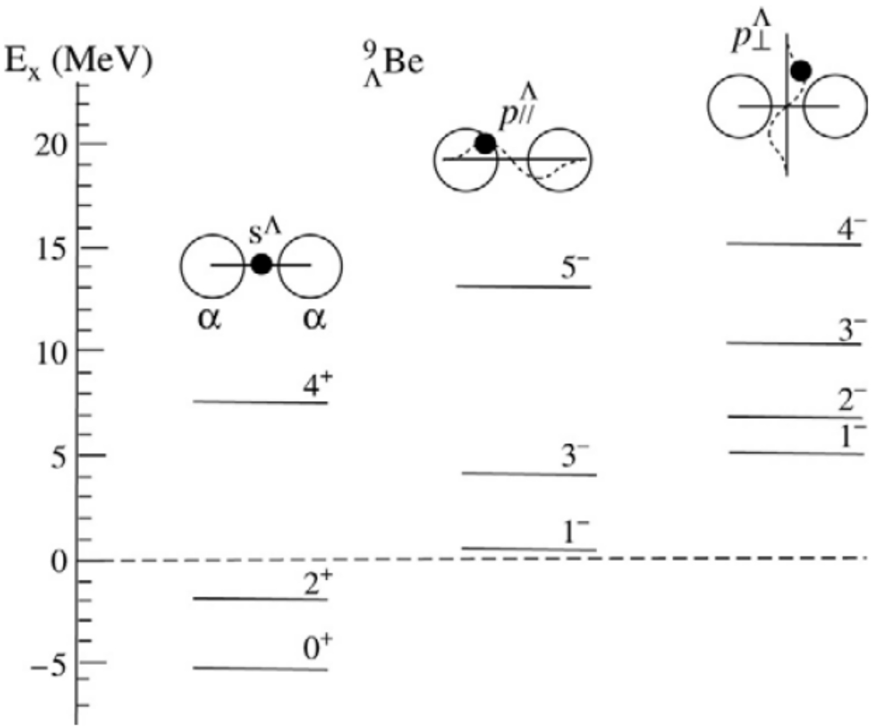


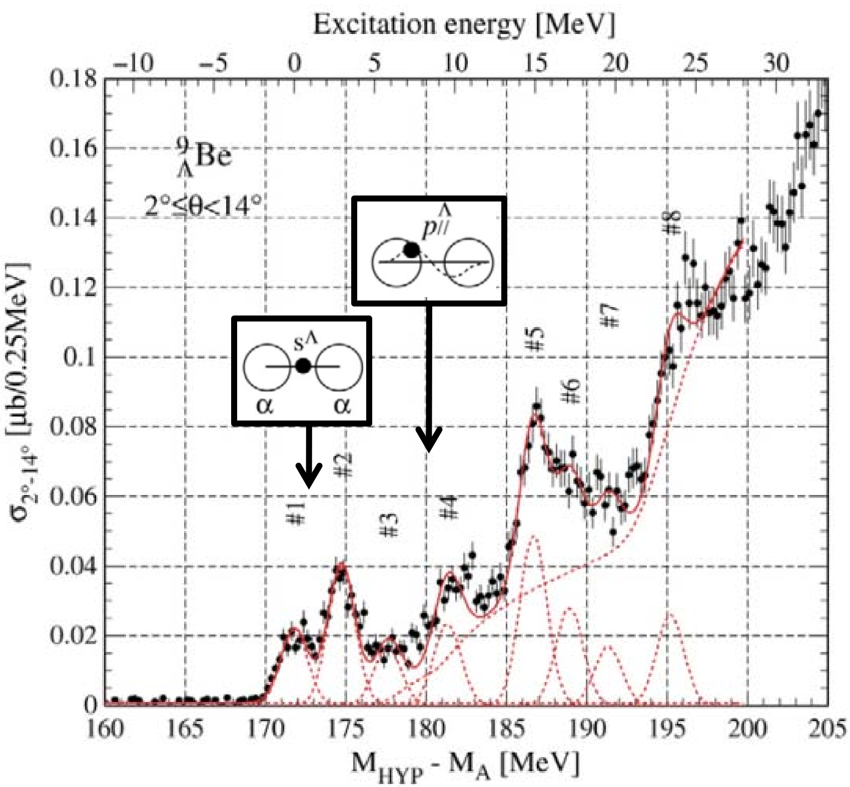
Example: *p*-states of $^{9}_{\Lambda}$Be

In case of $^{9}_{\Lambda}$Be with axially symmetric 2α clustering

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

→ **Λ hyperon in p orbit parallel to/perpendicular to the 2α clustering generates 2 different bands [1,2]**

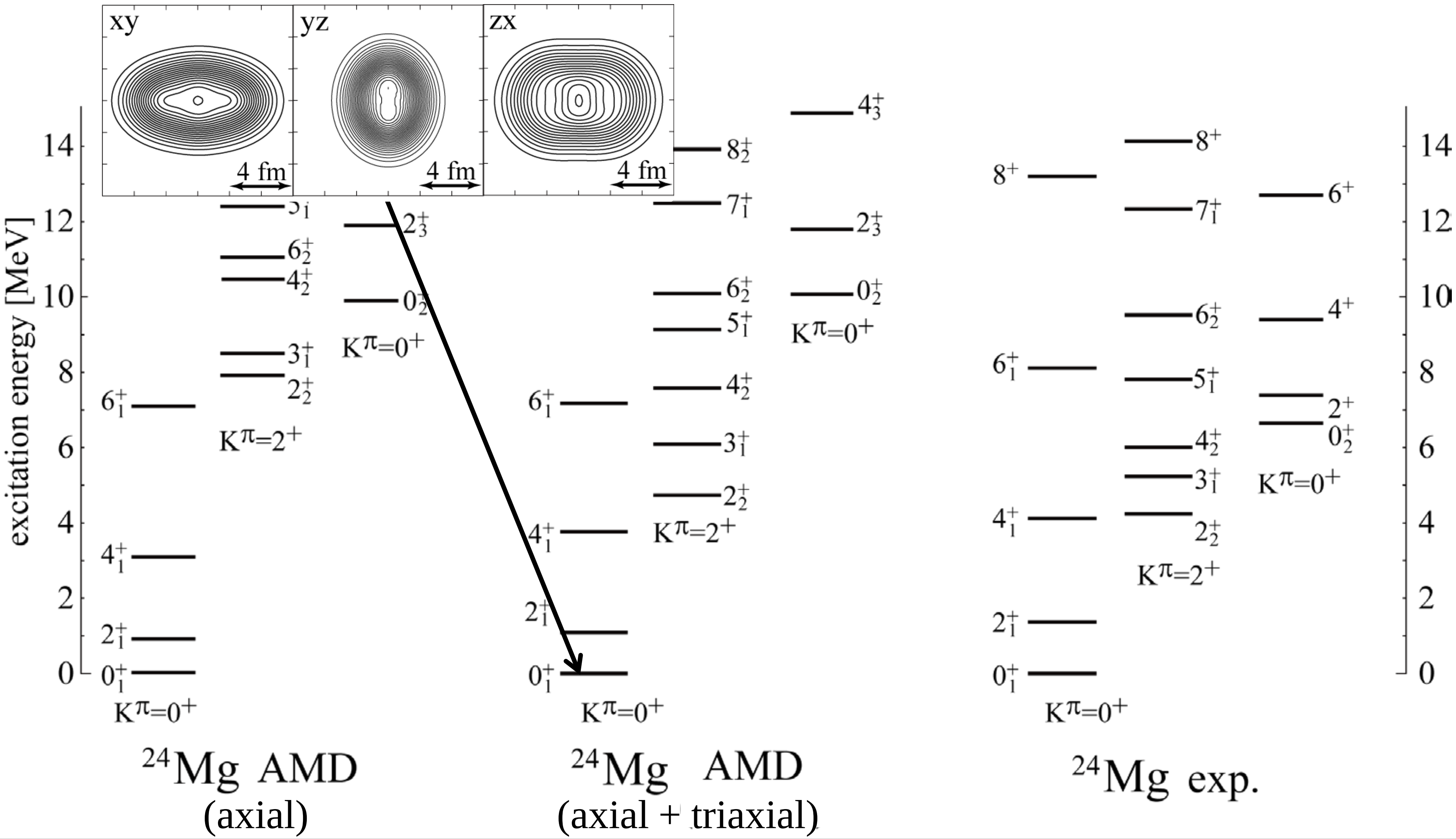




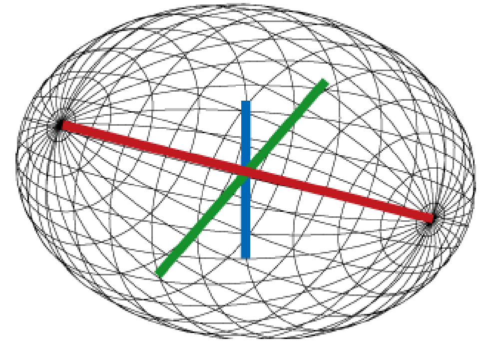
[1] H. Bando, et al., PTP **66** (1981) 2118.
[2] H. Bando, et al., IJMP **21** (1990) 4021.
[3] O. Hashimoto et al., NPA **639** (1998) 93c.

Deformation of ^{24}Mg

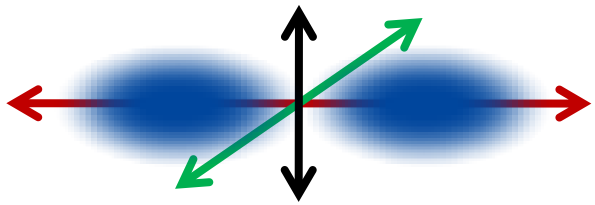
- ^{24}Mg is one of the candidates of triaxially deformed nuclei



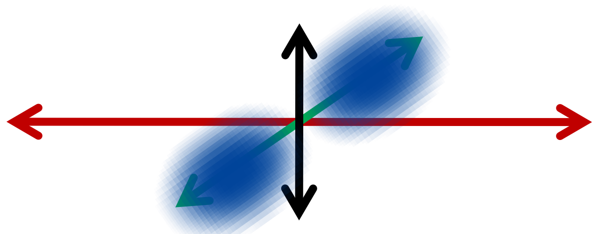
A Simple idea



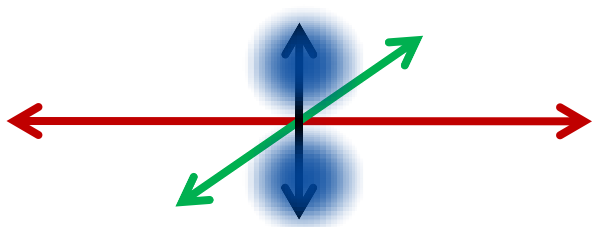
Triaxial deformation



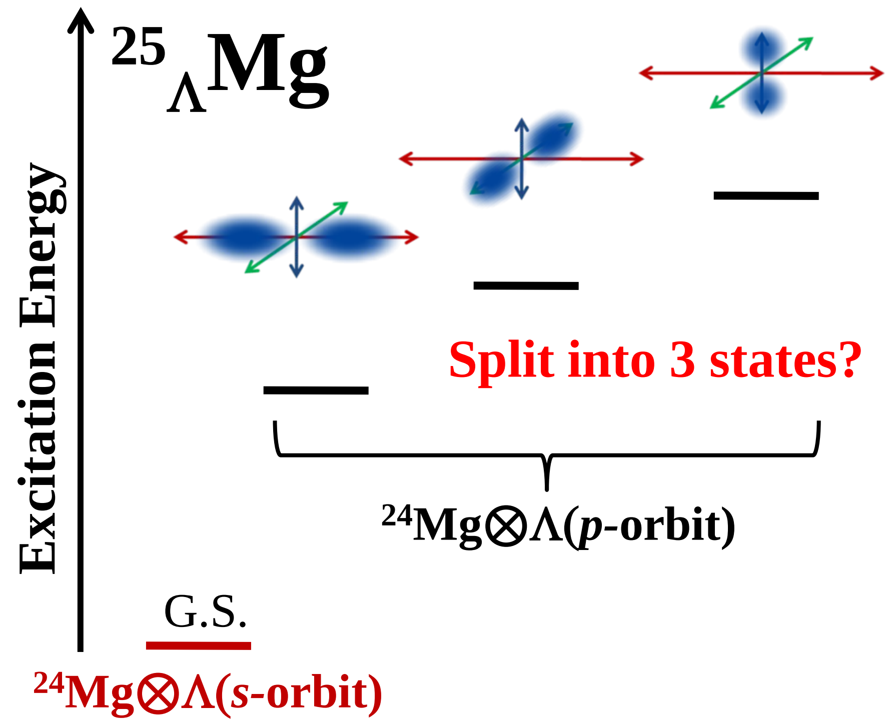
Large overlap leads deep binding



Middle



Small overlap leads shallow binding

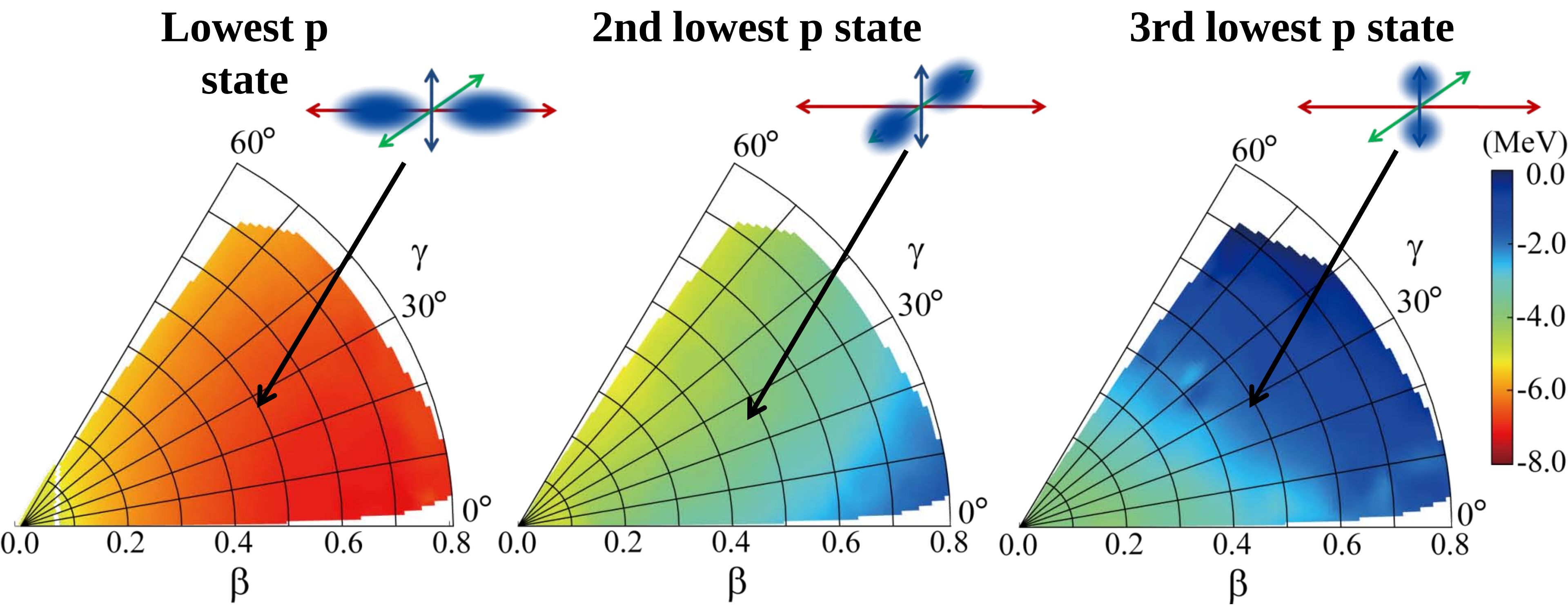


- **p-orbit states split into 3 different state**
- **Observing such 3 different states is strong evidence for triaxial deformation of ^{24}Mg**

Results： Single particle energy of Λ hyperon

Λ single particle energy on (β, γ) plane

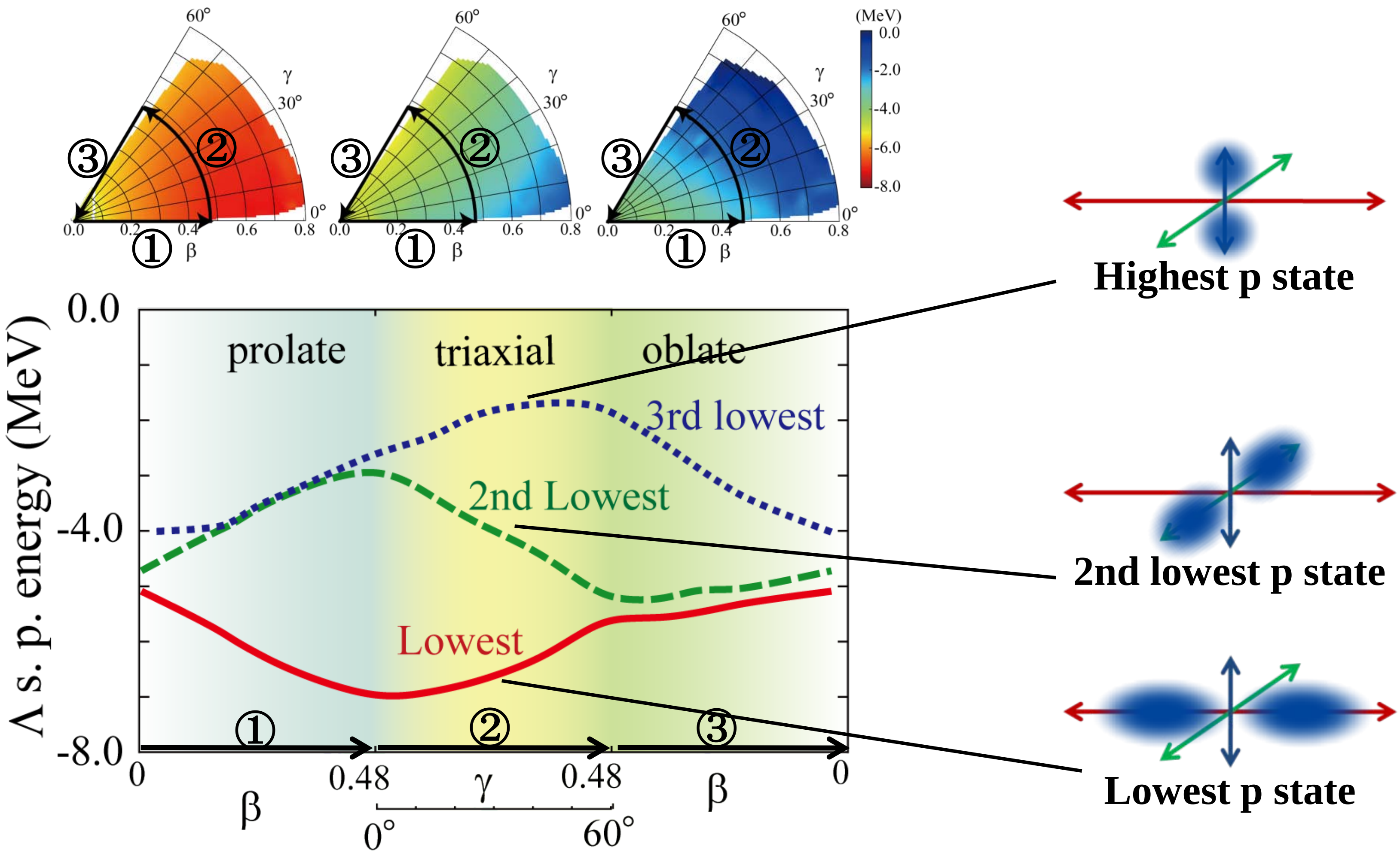
${}^{25}_{\Lambda}$Mg (AMD, Λ in *p* orbit)



- Single particle energy of Λ hyperon 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 in axial/triaxial deformed nucleus

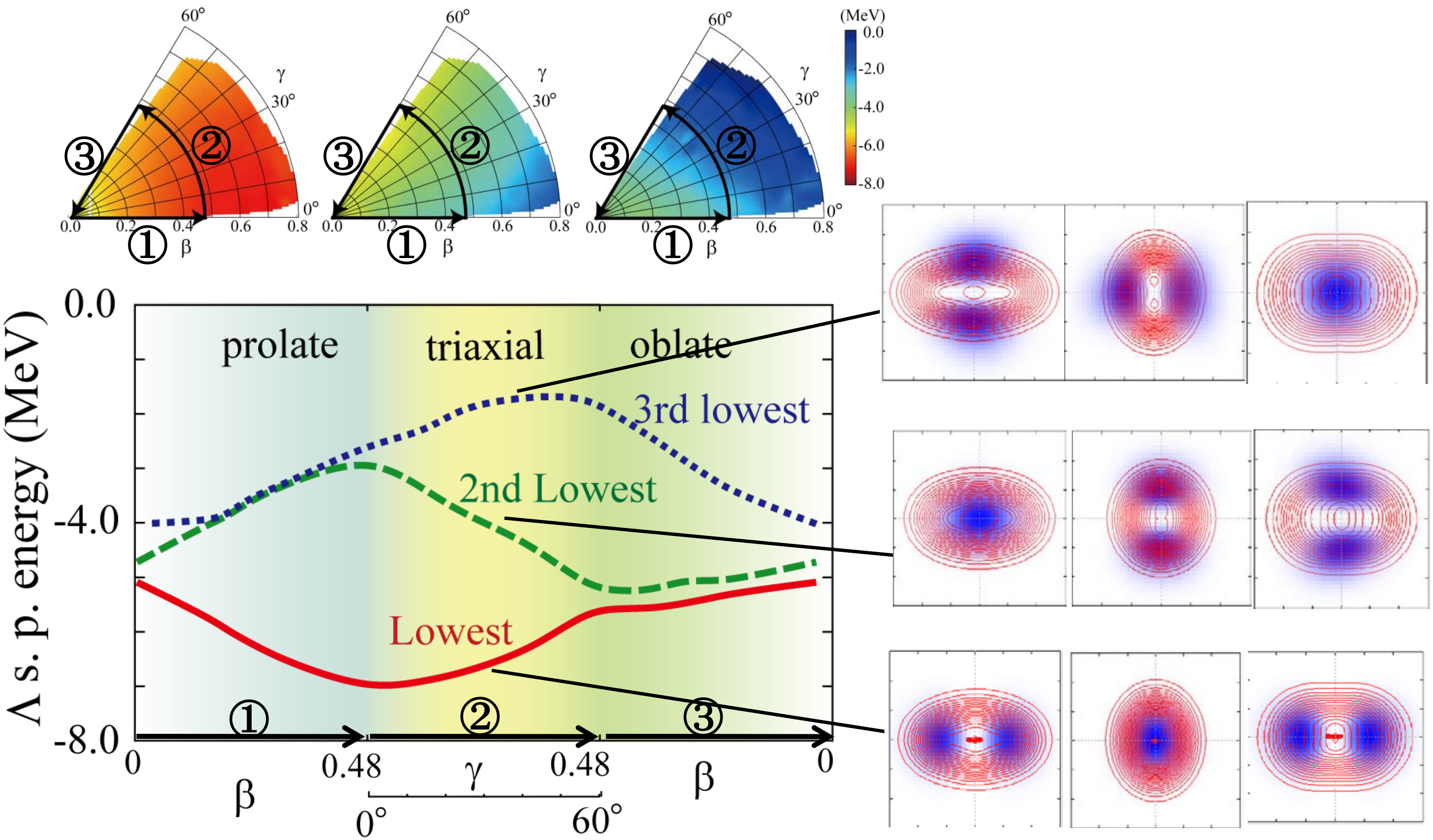


Λ s. p. energies are different from each other with triaxial deformation

⟶ split into 3 p-orbit states

Results： Single particle energy of Λ hyperon

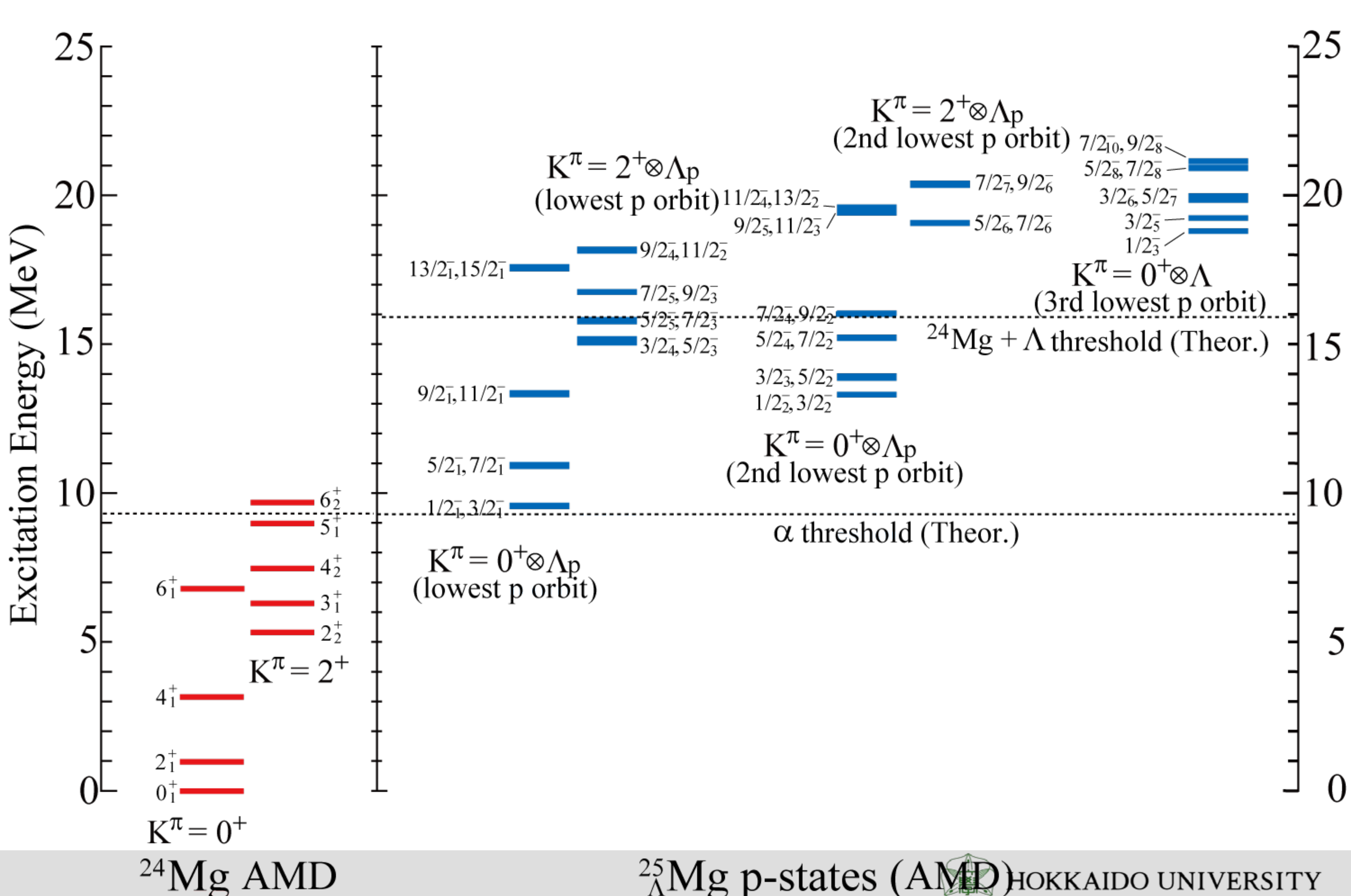
Λ single particle energy in axial/triaxial deformed nucleus



Λ s. p. energies are different from each other with triaxial deformation

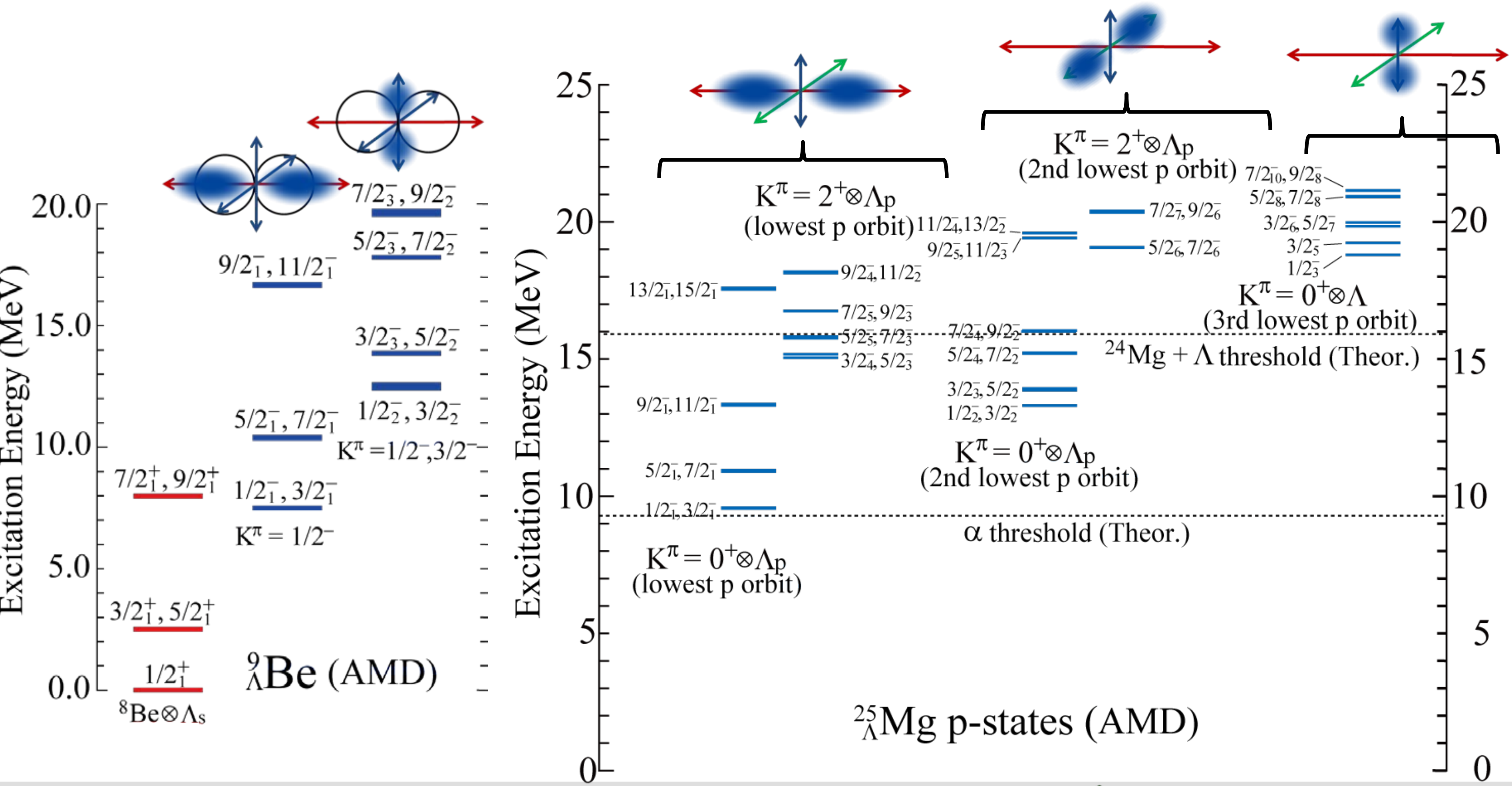
⟶ split into 3 p-orbit states

Results: Excitation spectra



Results: Excitation spectra

- ^{24}Mg⊗Λp(lowest), ^{24}Mg⊗Λp(2nd lowest), ^{24}Mg⊗Λp(3rd lowest) bands will be generated
- These correspond to the direction of the p-orbit



Summary

Knowledge on YN(YY) interaction will open new era of hypernuclear study

- Modifying nuclear structure using hyperons as an impurity
- Investigating nuclear structure using hyperons as an probe
- Bounding unbound systems using hyperons as a glue

Combination of the modern YN(YY) interactions and nuclear models

- Antisymmetrized molecular dynamics + effective YN interactions

Modifiying nuclear structure using Λ as an impurity

- Reduction of nuclear deformation by Λ in s-wave
- Parity reversion of $^{12}{}_{\Lambda}\mathrm{Be}$

Probing nuclear structure using Λ as an probe

- Splitting of p-waves in $^{25}{}_{\Lambda}\mathrm{Mg}$ due to the triaxial deformation