Nuclear deformation and $^{27}_{\Lambda}$Mg hypernucleus

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Grand challenges of hypernuclear physics

Interaction: "baryon-baryon interaction"

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

} Major issues in hypernuclear physics

Structure: "many-body system of nucleons and hyperon"

- **Addition of hyperon as an impurity in (hyper)nuclei**
  - No Pauli exclusion between N and Y
  - YN interaction is different from NN

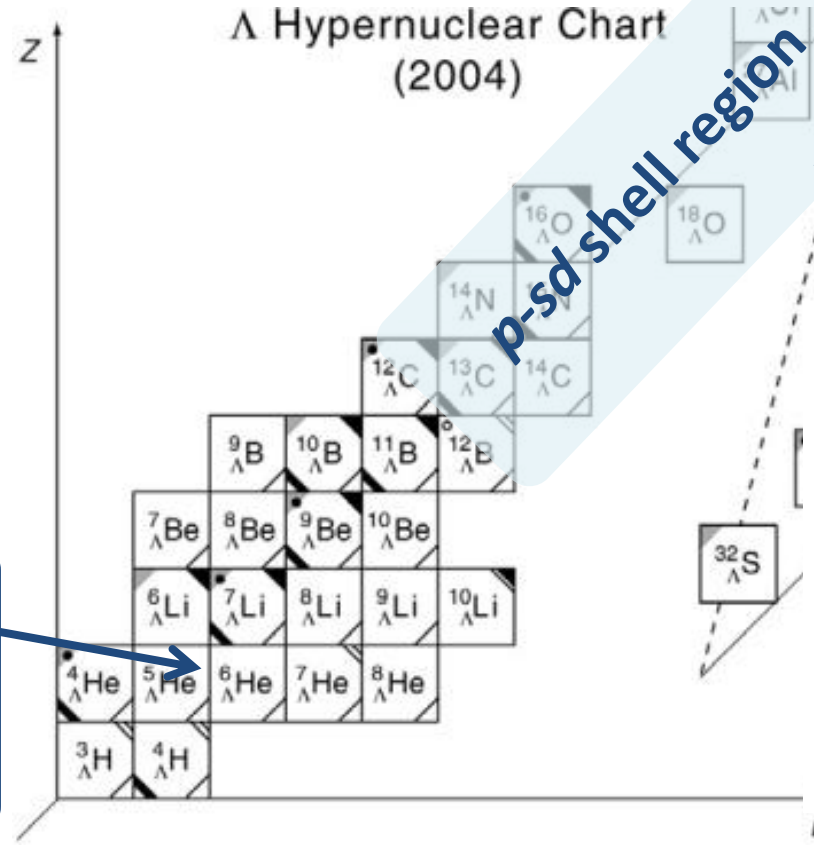
→ Structure changes
Unique structure, … etc.

Today: "deformation of hypernuclei"

Toward heavier and exotic Λ hypernuclei

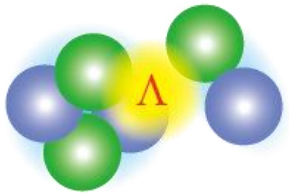
◆Experiments at J-PARC, JLab, *etc*.

- **Heavier(*sd*-shell and more) hypernuclei can be produced**
- **Various structures will appear**



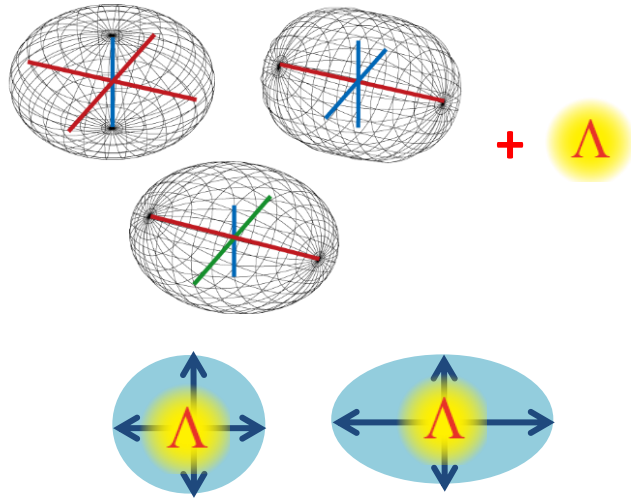
cf. Light hypernuclei

Developed cluster



Various deformations

- coexistence of deformations
- largely deformed states
- triaxial deformation, … etc.



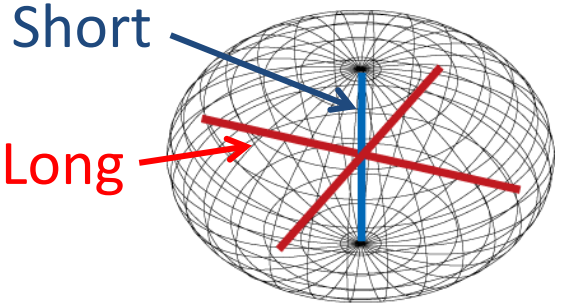
Today: "deformation of hypernuclei"

Deformation of nuclei

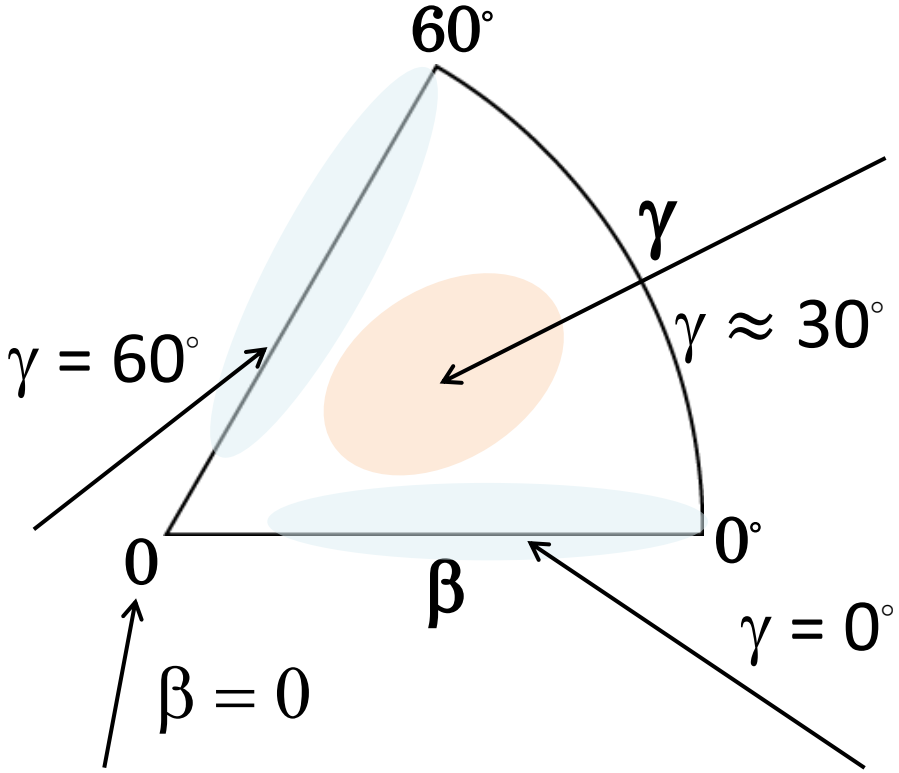
◆Most of nuclei are deformed except for magic nuclei

●Nuclear quadruple deformation (β,γ)

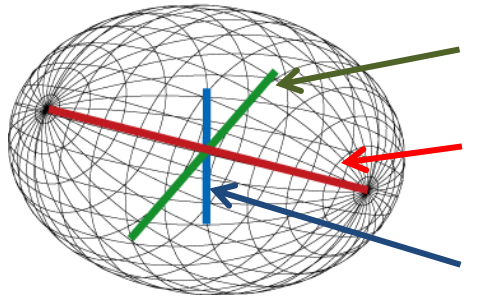
- β: degree of quadrupole deformation
- γ: (tri)axiality



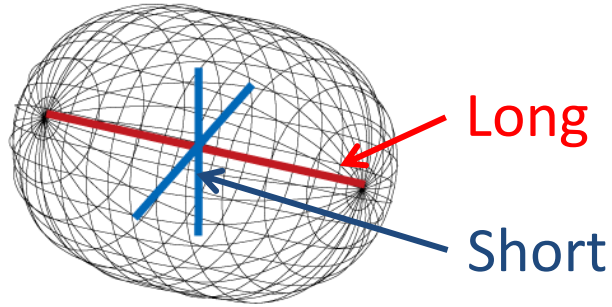
Oblate deformation
short axis symmetry
Example: ^{12}C, ^{28}Si



Spherical
Example: magic nuclei



Triaxial deformation
no symmetry axis
Candidate: ^{26}Mg



Prolate deformation
long axis symmetry
Example: ^{20}Ne

What is expected in deformed Λ hypernuclei

- **Deformation change**
  - Λ particle can change nuclear deformation
- **Difference of B_Λ depending on nuclear deformation**
  - Energy shifts in excitation spectra
- **Coupling of Λ to deformed nuclei shows unique structure**
  - For example, rotational band, mixing of configuration, … etc.

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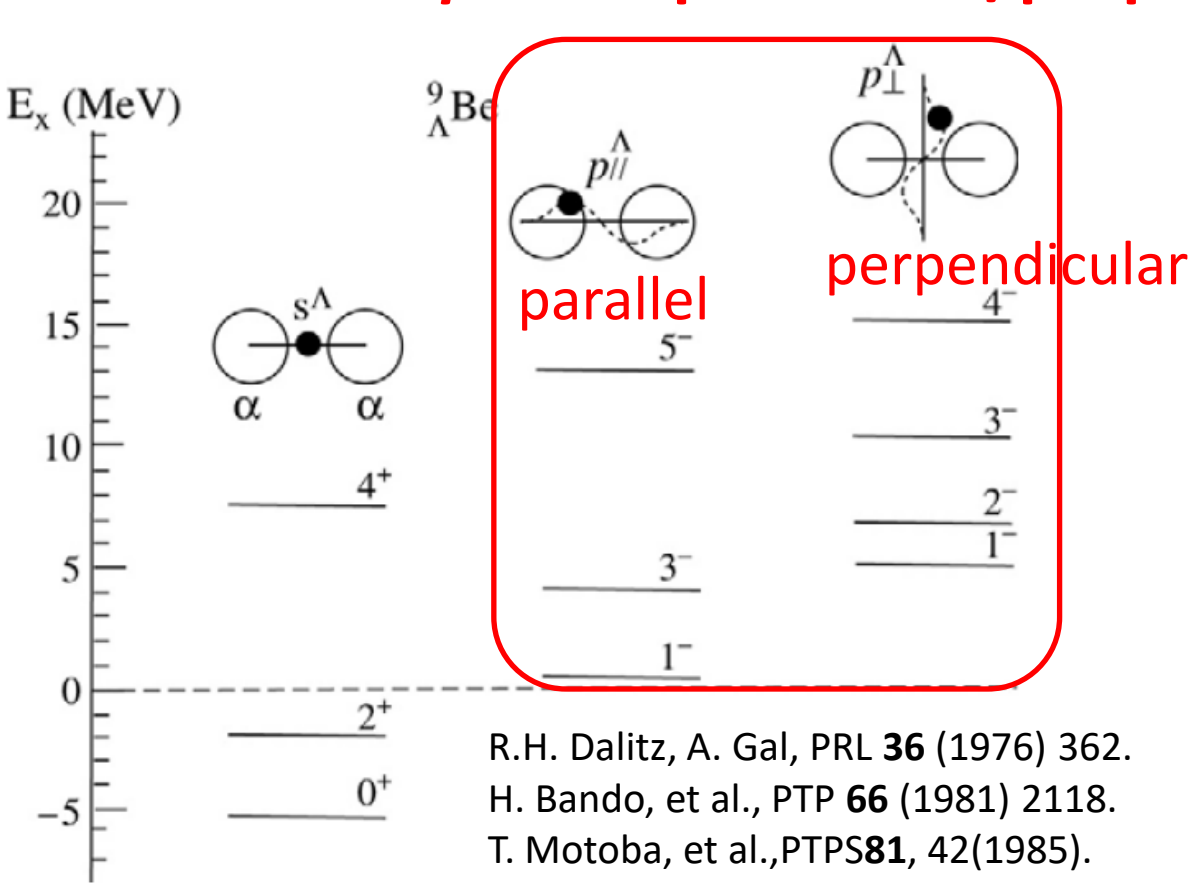
Coupling of Λ in *p*-orbit: *p*-states of $^{9}_{\Lambda}$Be

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

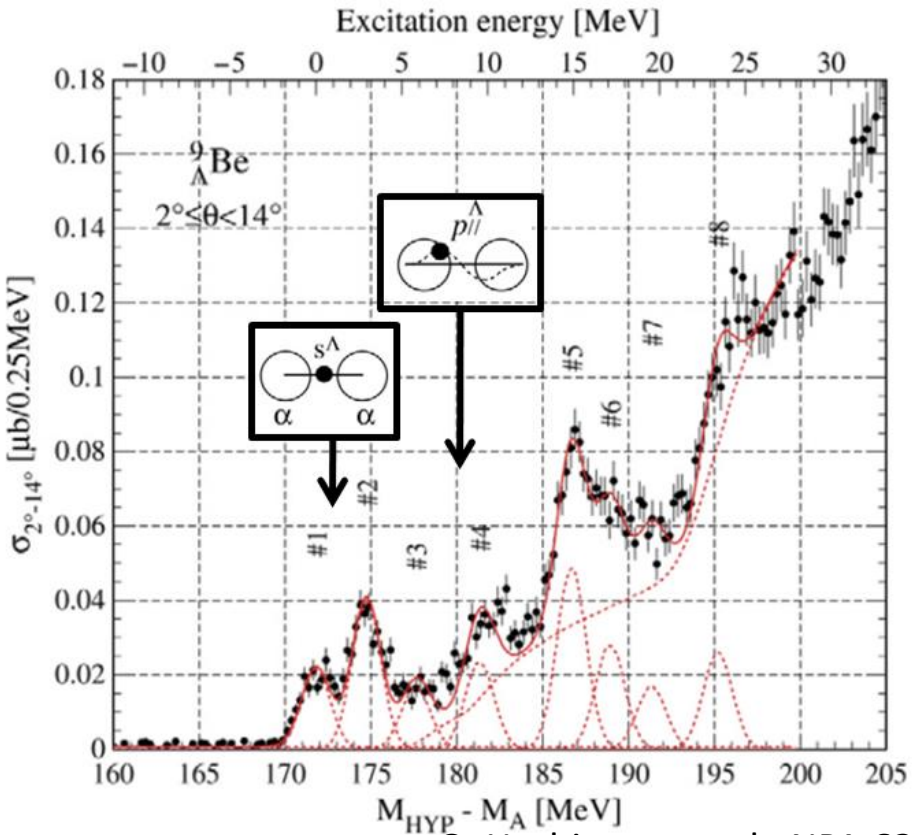
Two rotational bands as *p*-states

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

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



R.H. Dalitz, A. Gal, PRL **36** (1976) 362.
H. Bando, et al., PTP **66** (1981) 2118.
T. Motoba, et al.,PTPS**81**, 42(1985).



O. Hashimoto et al., NPA **639** (1998) 93c.

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

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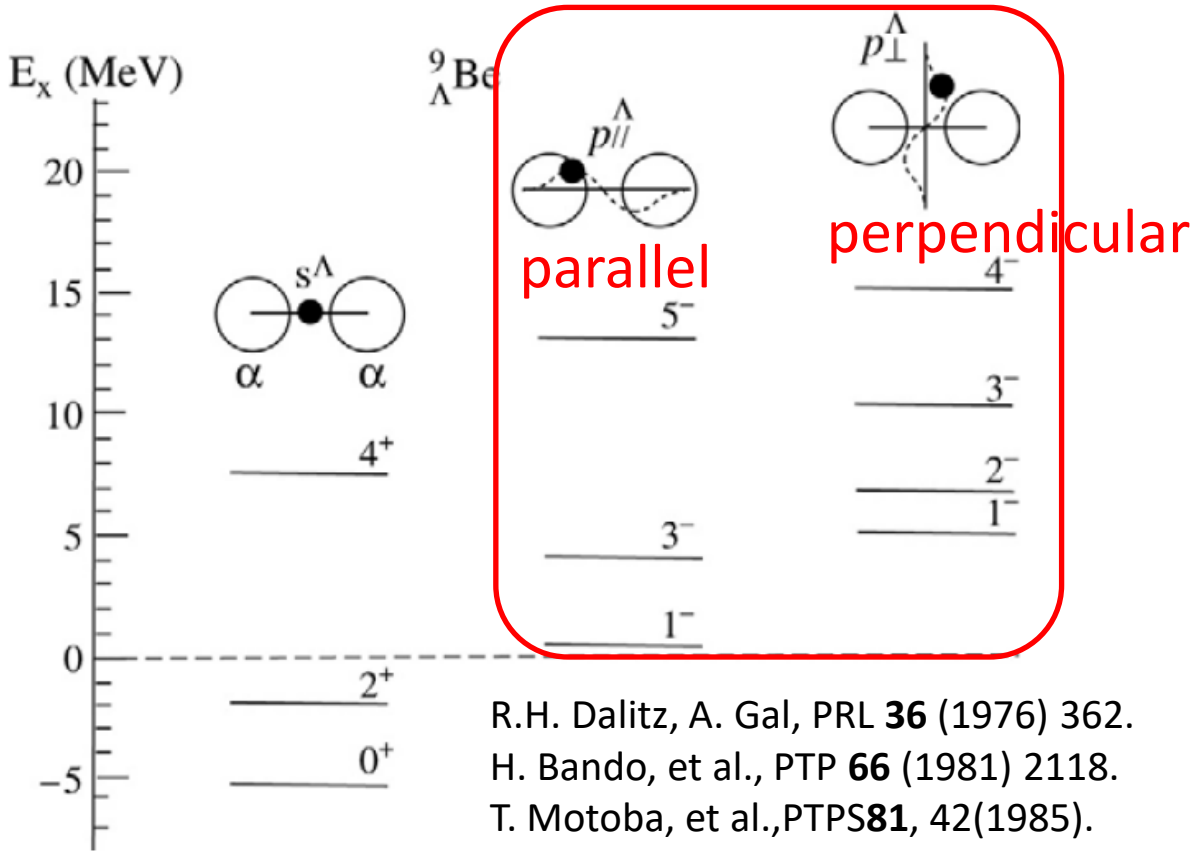

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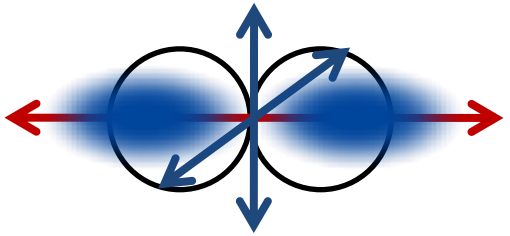
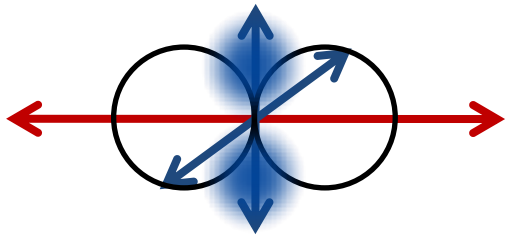
***p* orbit parallel to 2α (long axis)**



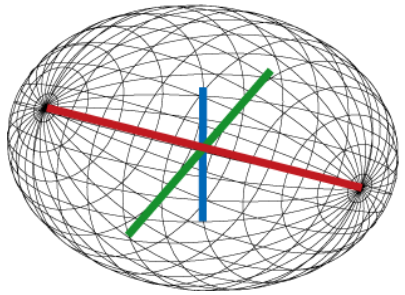
Large overlap
Deeply bound

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

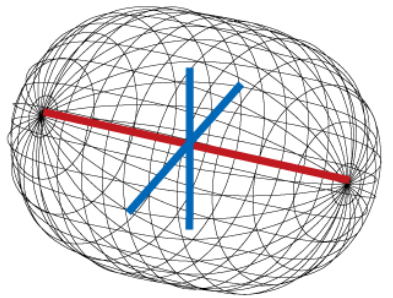


Small overlap
Shallowly bound

Triaxial deformation

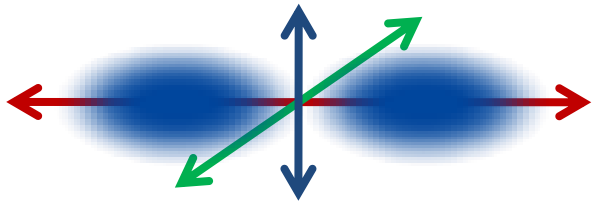


Triaxial deformation

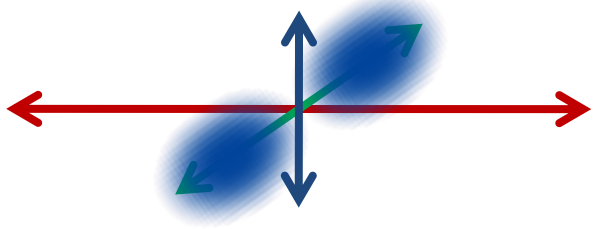


Prolate deformation

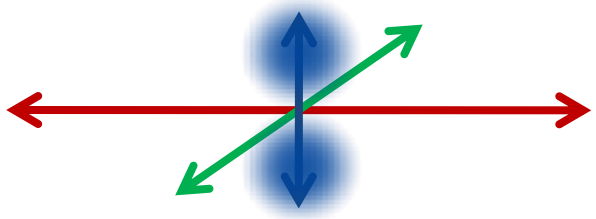
If nucleus is triaxially deformed,
***p*-states can split into 3 different state**



Large overlap
Deeply bound

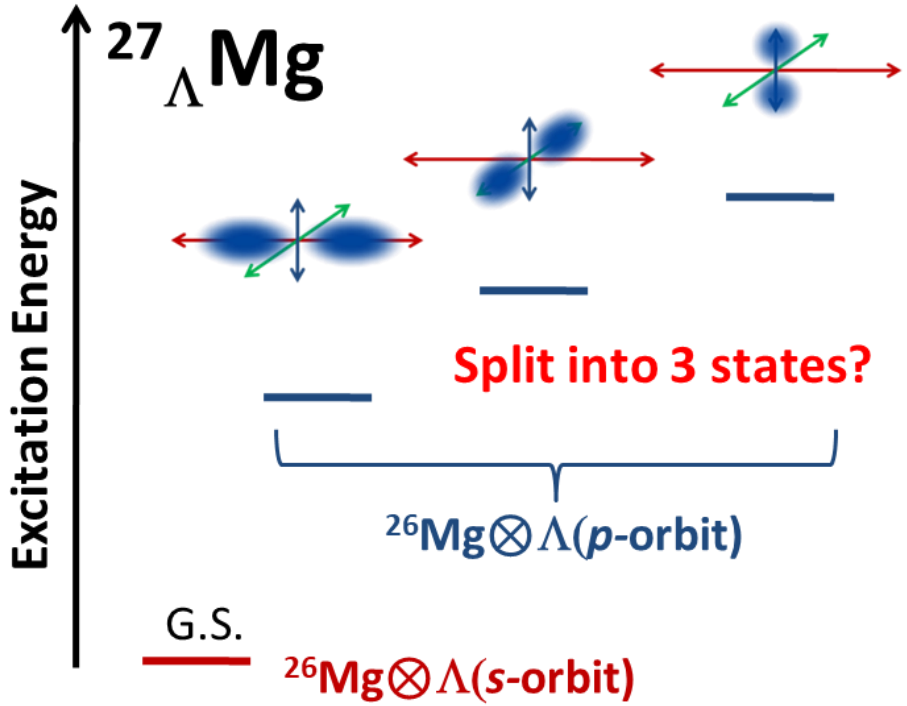


Middle



Small overlap
shallow binding

Candidate: Mg hypernuclei



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

What is expected in deformed Λ hypernuclei

- **Deformation change**
  - **Λ particle can change nuclear deformation**
- **Difference of B_Λ depending on nuclear deformation**
  - **Energy shifts in excitation spectra**
- **Coupling of Λ to deformed nuclei shows unique structure**
  - **For example, rotational band, mixing of configuration, … etc.**

Today
- triaxial deformation of Mg nuclei: $^{27}_{\Lambda}$Mg, future exp at JLab
- Rotational bands by Λ in p orbit coupled to the core

Theoretical Framework: HyperAMD

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

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, Volkov No.2
ΛN : YNG interaction (ESC14)

◆Wave function

- **Nucleon part : Slater determinant**
  Spatial part of s.-p. w.f. is described as Gaussian packets

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

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

$$\chi_i = \alpha_i \chi_\uparrow + \beta_i \chi_\downarrow$$

- **Single-particle w.f. of Λ hyperon:**
  Superposition of Gaussian packets

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

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

$$\chi_m = a_m \chi_\uparrow + b_m \chi_\downarrow$$

- **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

M.I., *et al.*, PRC**83**(2011) 044323
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◆Procedure of the numerical calculation

Variation

- 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 intrinsic wave functions with different configuration
- Diagonalization of $H^{J\pm}_{sK,s'K'}$ and $N^{J\pm}_{sK,s'K'}$

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

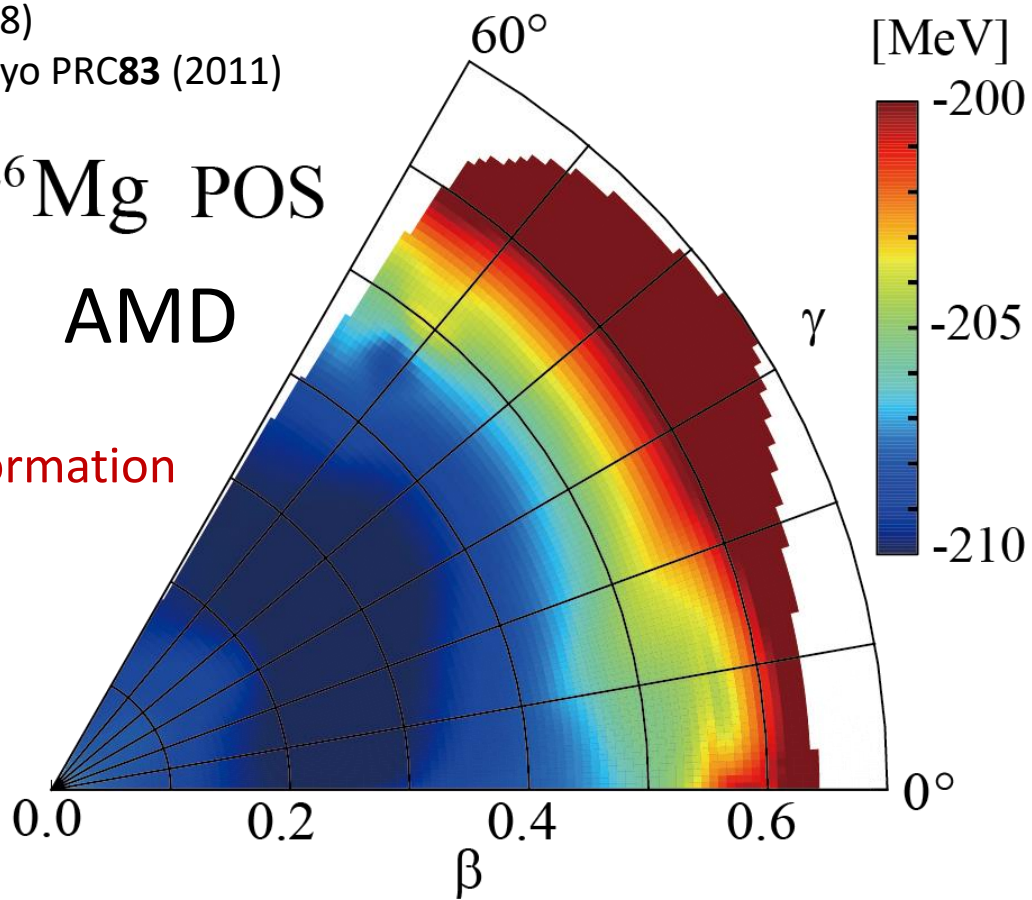
$$N^{J\pm}_{sK,s'K'} = \left\langle \Phi_K^s; J^{\pm}M \middle| \Phi_{K'}^{s'}; J^{\pm}M \right\rangle$$

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

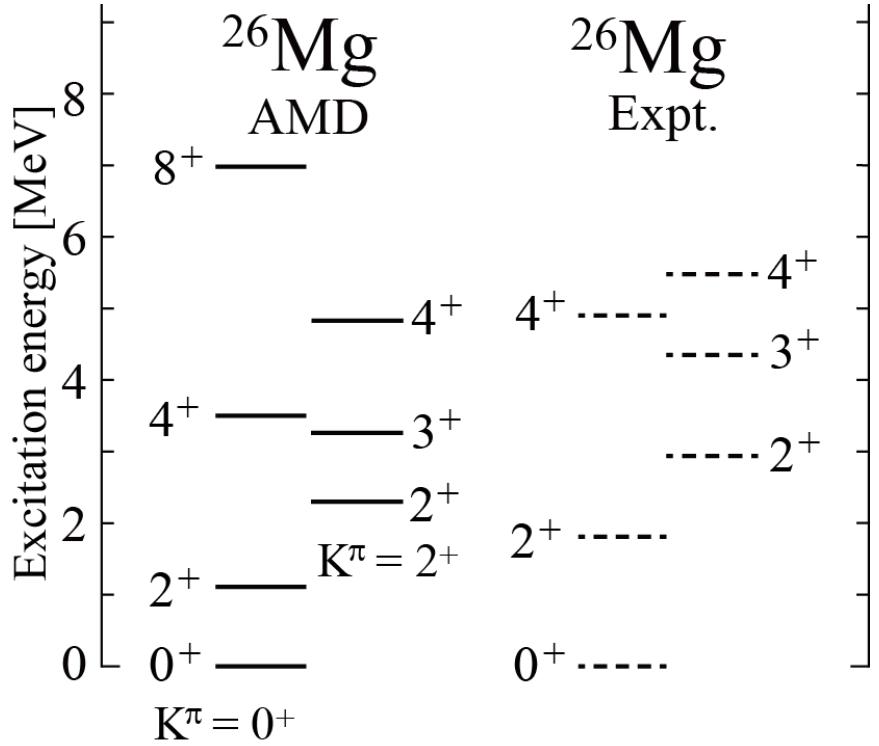
Deformation of ^{26}Mg

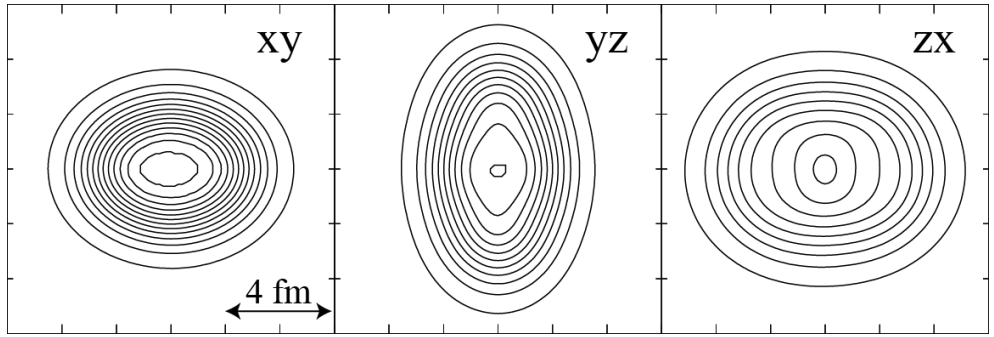
- Shell gap in Nilsson diagram: Z=12 (prolate) vs. N=14 (oblate) → triaxial
- β,γ-softness is discussed by several authors

Terasaki et al. NPA**621**(1997)
Rodrıguez-Guzman et al. NPA**709** (2002)
Peru et al PRC**77** (2008)
Hinohara, Kanada-En'yo PRC**83** (2011)



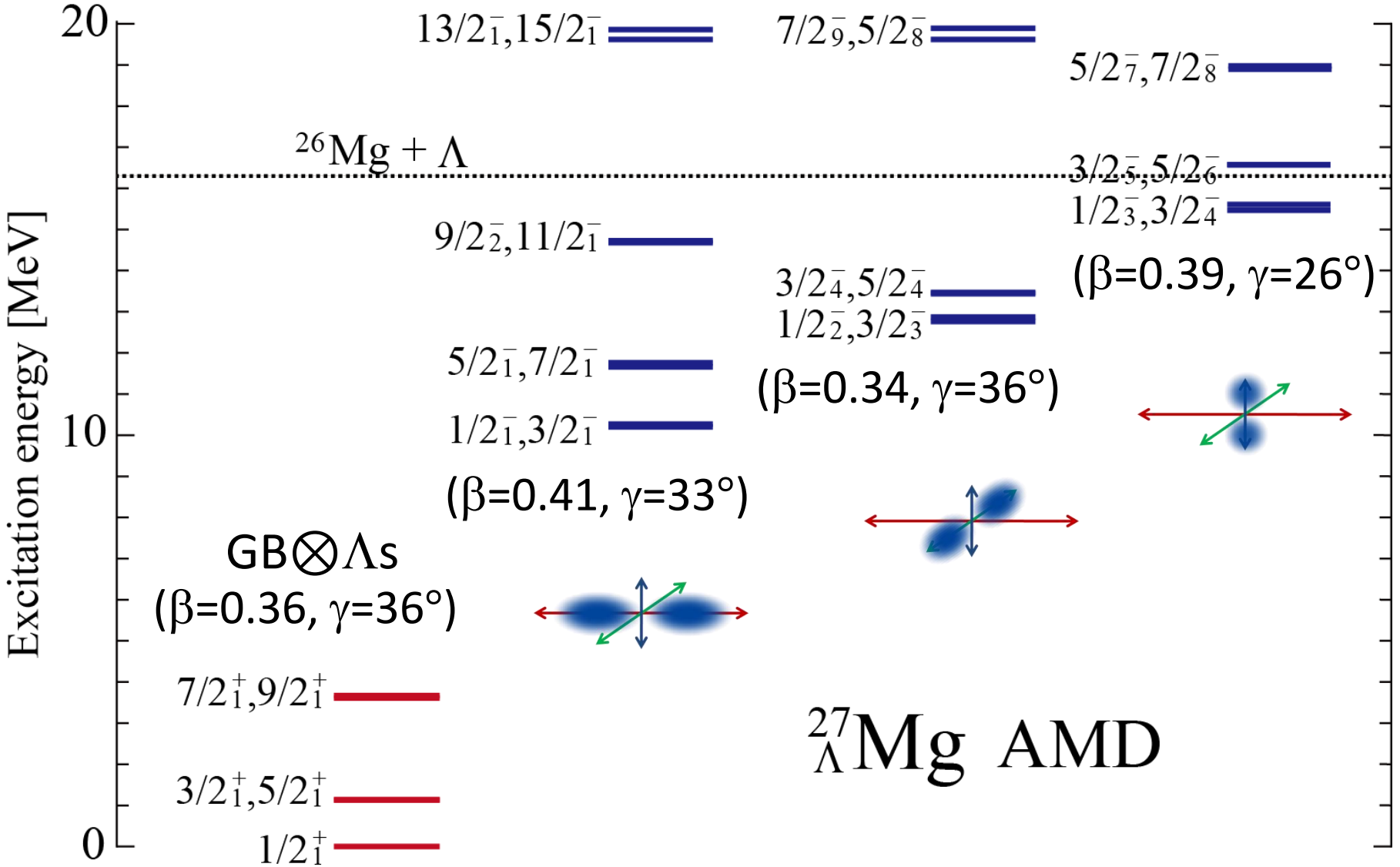
β: degree of deformation
γ: (tri)axiality





Results: $^{27}_{\Lambda}$Mg

- **3 bands are obtained by Λ in *p*-orbit → Splitting of the *p* states**

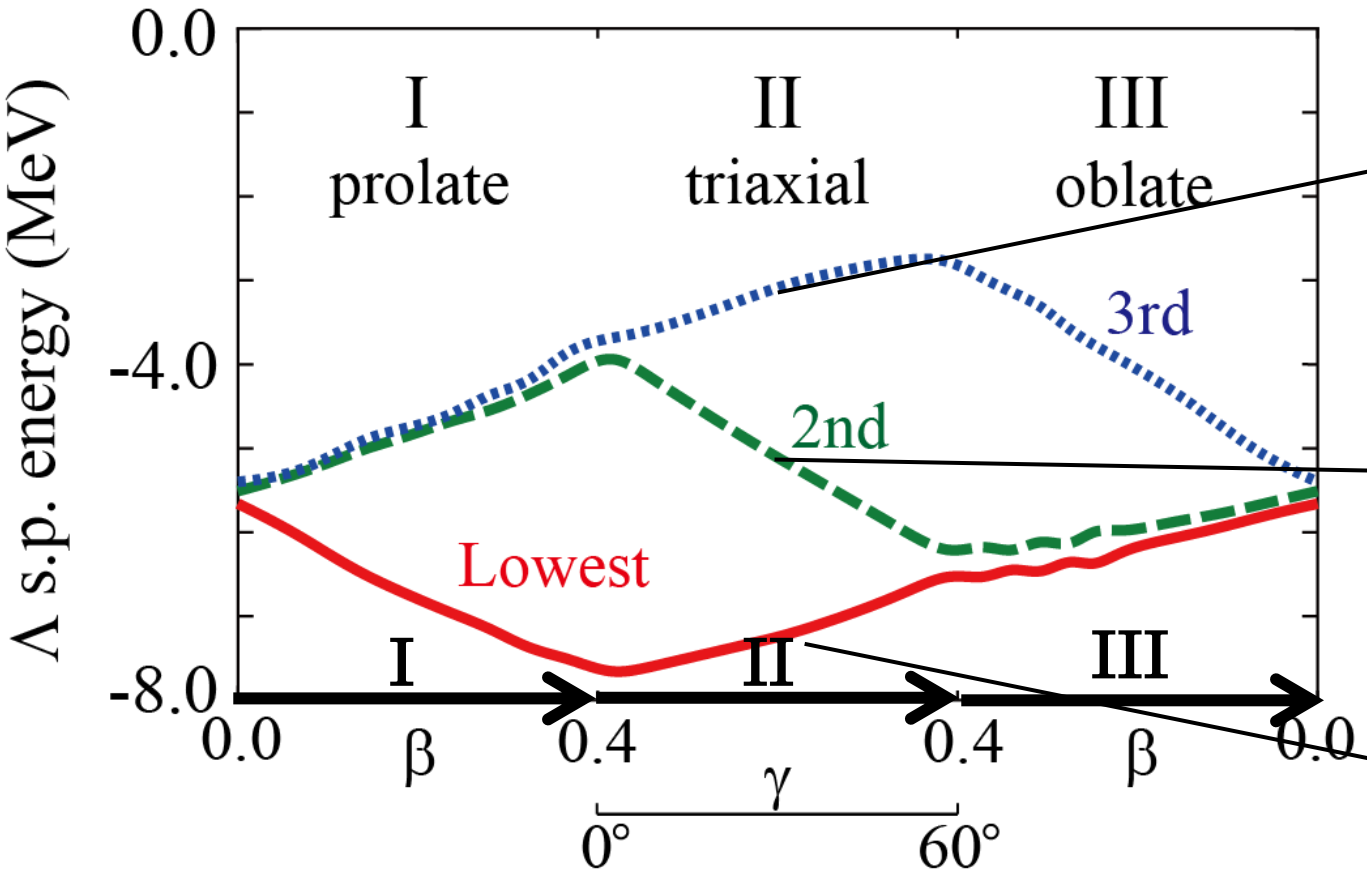


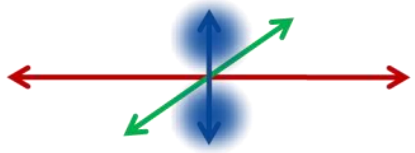
cf. ^{26}Mg ground state:
β=0.41, γ=33°

Results : Single particle energy of Λ hyperon ε_Λ

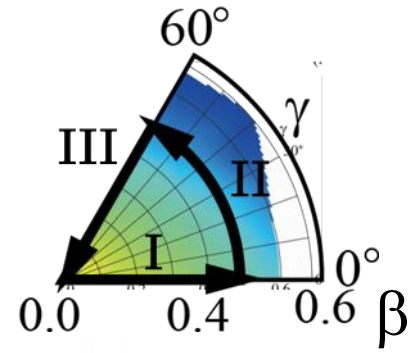
$^{27}_{\Lambda}$Mg (AMD)

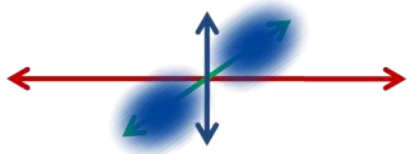
$$\varepsilon_\Lambda(\beta,\gamma) = E_{\Lambda p}(\beta,\gamma) - E_{core}(\beta,\gamma)$$



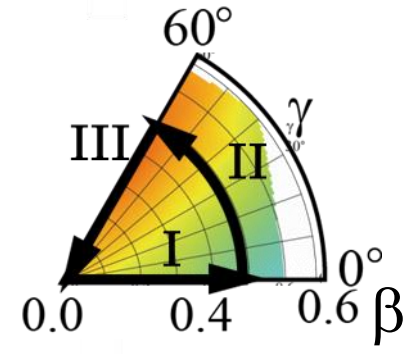


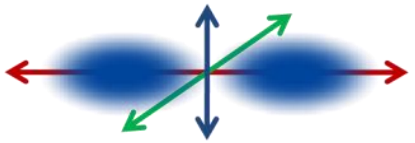
3rd lowest



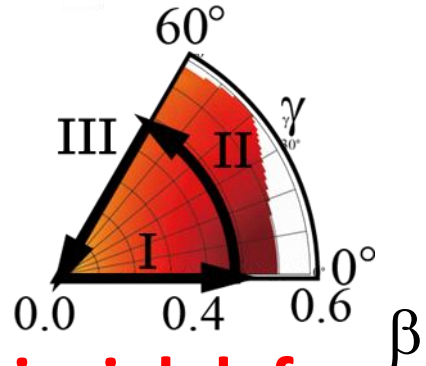


2nd lowest





Lowest



- **Λ single-particle energy is different in each p orbit with triaxial deformation**
- **3 different p-states appear if the core nucleus is triaxially deformed**

Summary and Future problems

◆Hypernuclear deformation

- **Deformation change by Λ particle**
- **Difference of B_Λ depending on deformation**
- **Coupling of Λ to deformed nuclei**
  - Today's topic: *p*-states in triaxially deformed Mg hypernuclei

◆Study of ^{26}Mg: possibility to use Λ as a probe of deformation

- **Detailed analysis: $\beta\gamma$-dep., rotational bands, B(E2), … etc.**
- **Production cross section: how to identify?**
- **Furthermore: deformation change, $\beta(\gamma)$-softness, … etc.**