分子動力学法を使った計算から解明するハイパー核の面白い側面って？

井坂 政裕（法政大）

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

  } → **"Impurity effects"**

Today: ハイパー核構造。Λが核に加わると、何が起こるか？

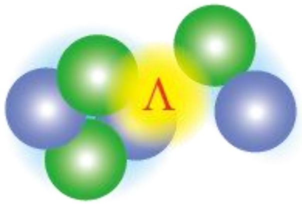
Structure of Λ hypernuclei

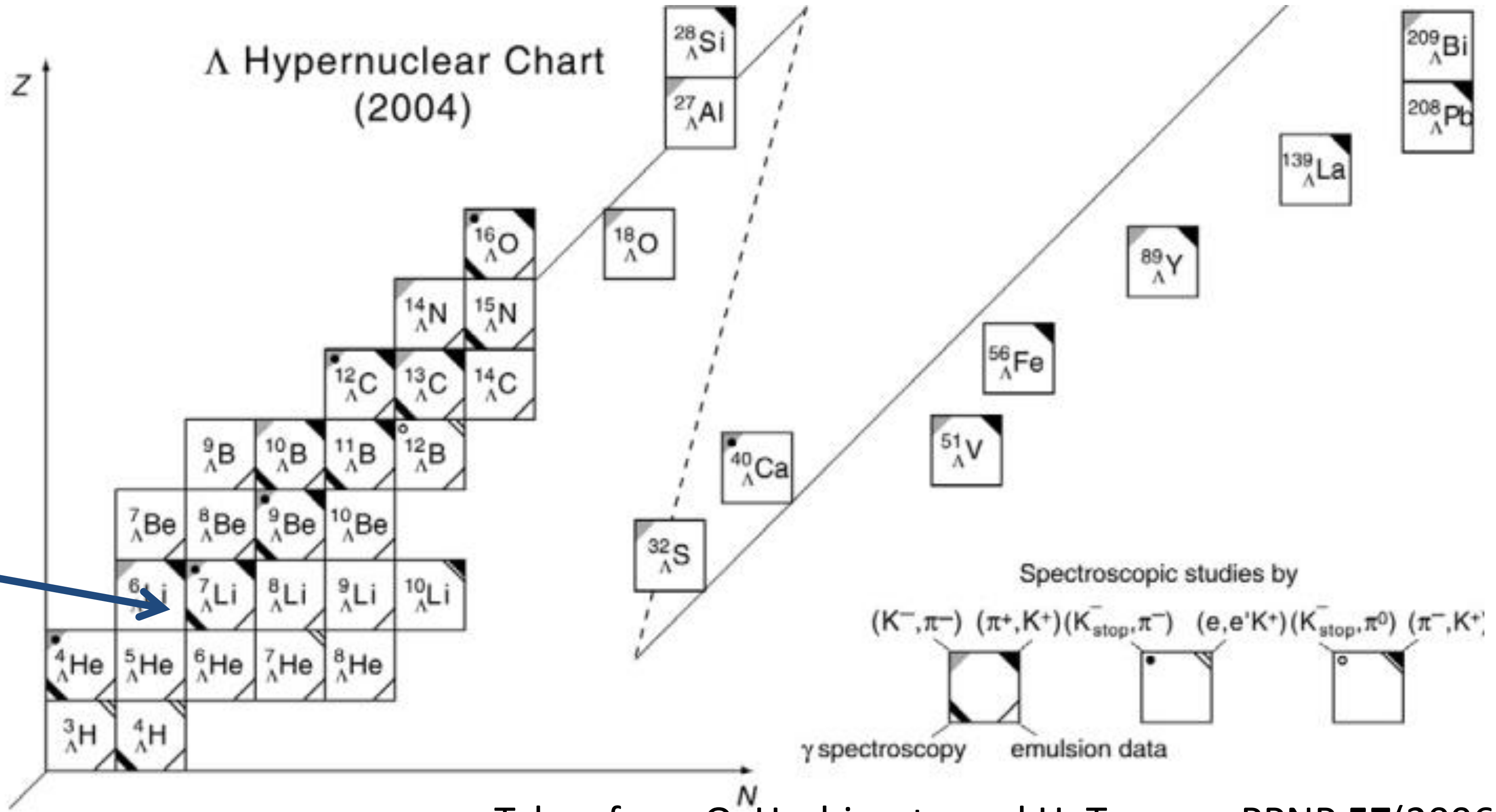
◆Λ hypernuclei observed so far

- **Concentrated in light Λ hypernuclei**
- **Most have well-developed cluster structure**

Light Λ hypernuclei

Developed cluster





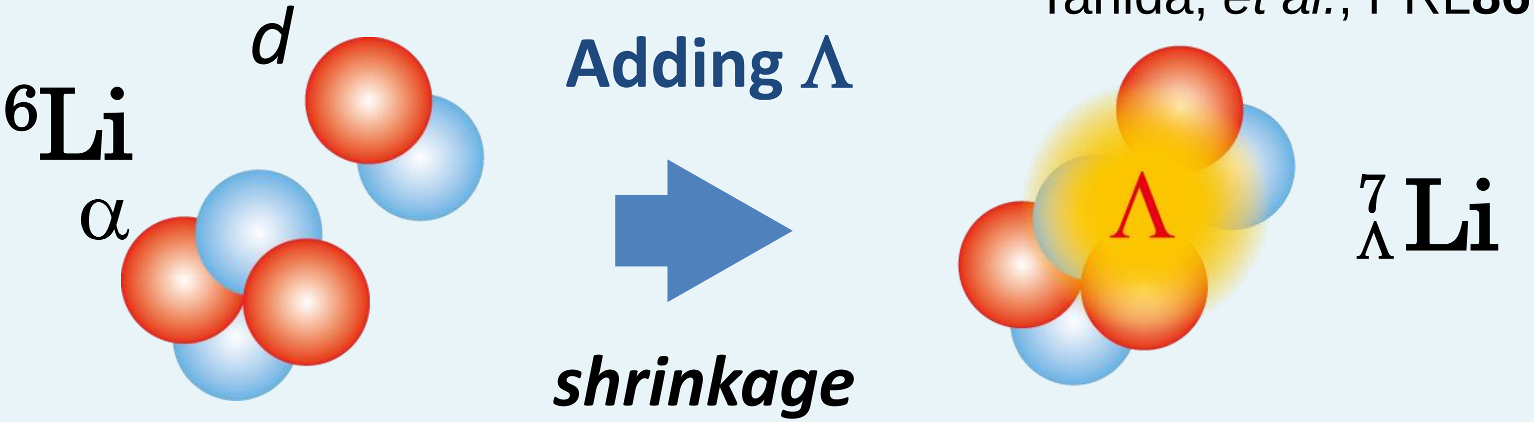
Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Cluster structure in light hypernuclei

◆Famous example of "impurity effect"

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

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



- Λ reduces inter-cluster distance b/w α + *d* of the core nucleus ^{6}Li
- Confirmed through B(E2) reduction

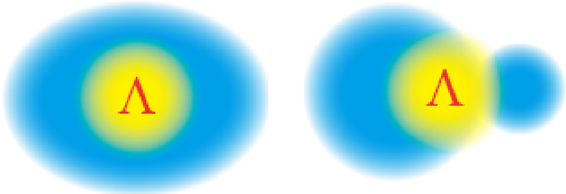
- Λ粒子によって、どのようなimpurity effectが起こるのか？
- 他の核でも同様のshrinkageが起こるのか？別の変化が起こるのか？

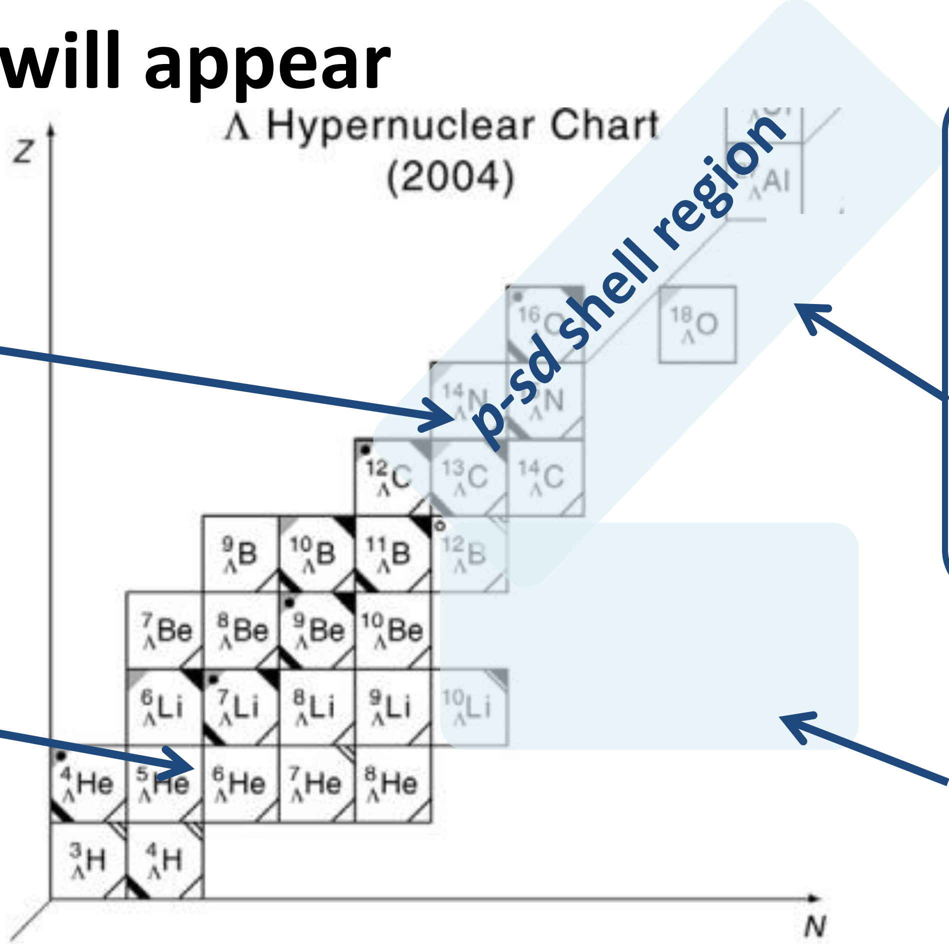
Toward heavier and exotic Λ hypernuclei

◆Experiments at J-PARC, JLab, *etc.*

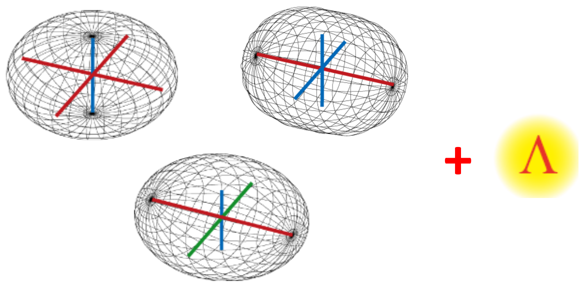
- **Heavier(*sd*-shell and more) hypernuclei can be produced**
- **Various structures will appear**

Coexistence of structures



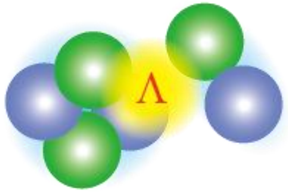


Various deformations

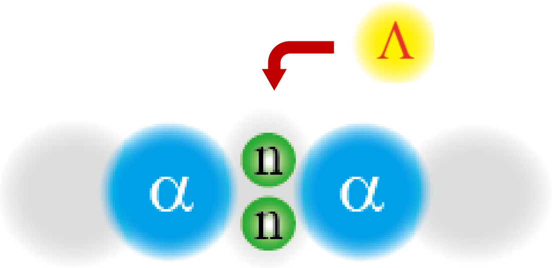


Light Λ hypernuclei

Developed cluster

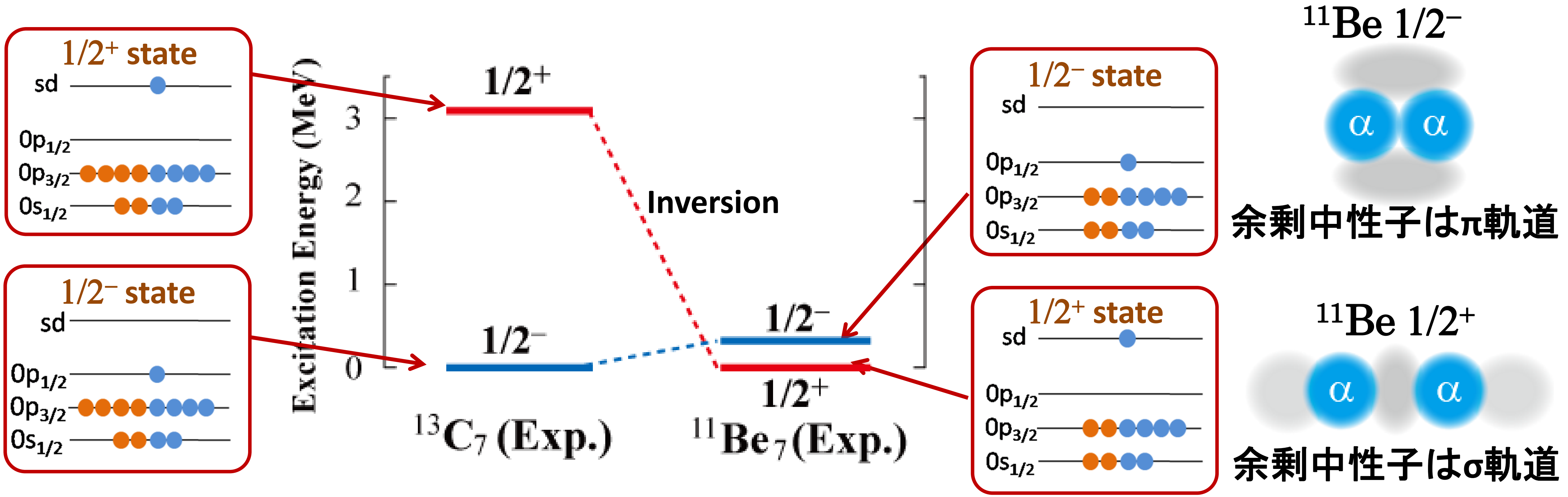


Exotic structure



Exotic structure of neutron-rich nuclei

◆Example :Parity inversion of the ^{11}Be g.s. → 魔法数N=8の消失



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

Λ粒子が加わると何が起こる？

- 各状態の構造をどれほど変えるのか？
- エネルギー準位（励起スペクトル）の変化は？

Structure of *sd*-shell nuclei

◆sd-shell核の構造の特徴

- 平均場構造とクラスター構造が低励起状態に共存

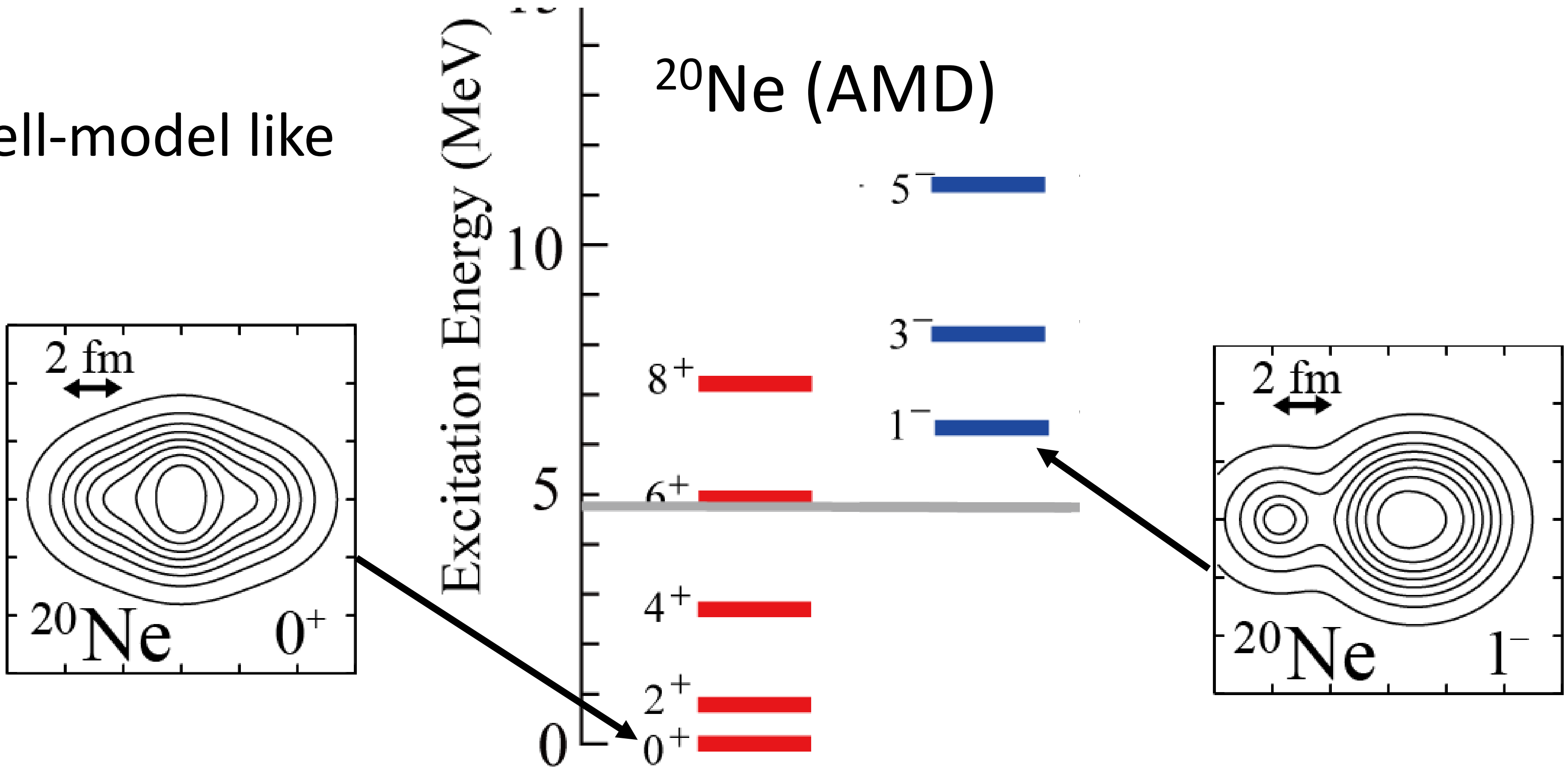
- 様々な変形：プロレート、オブレート、三軸非対称、超変形、etc.

Structure of *sd*-shell nuclei

◆Coexistence of mean-field like & cluster structures

Example: ^{20}Ne

- (Deformed) shell-model like
- α + ^{16}O cluster

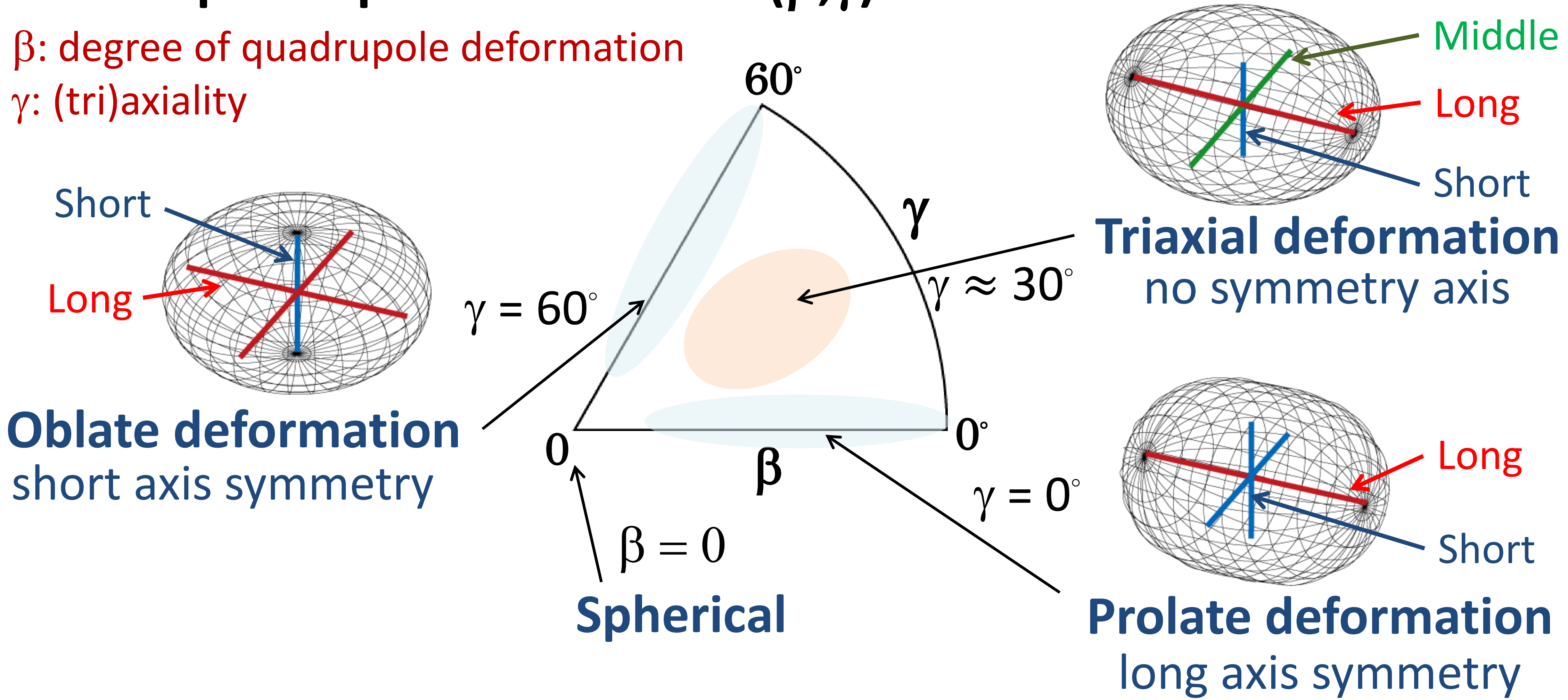


- 構造が異なる状態では、impurity effectsに違いはあるか？
- shrinkageは起こるのか？

Various 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



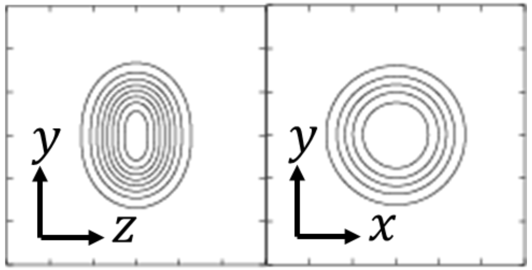
Various deformation of nuclei

◆Most of nuclei are deformed except for magic nuclei

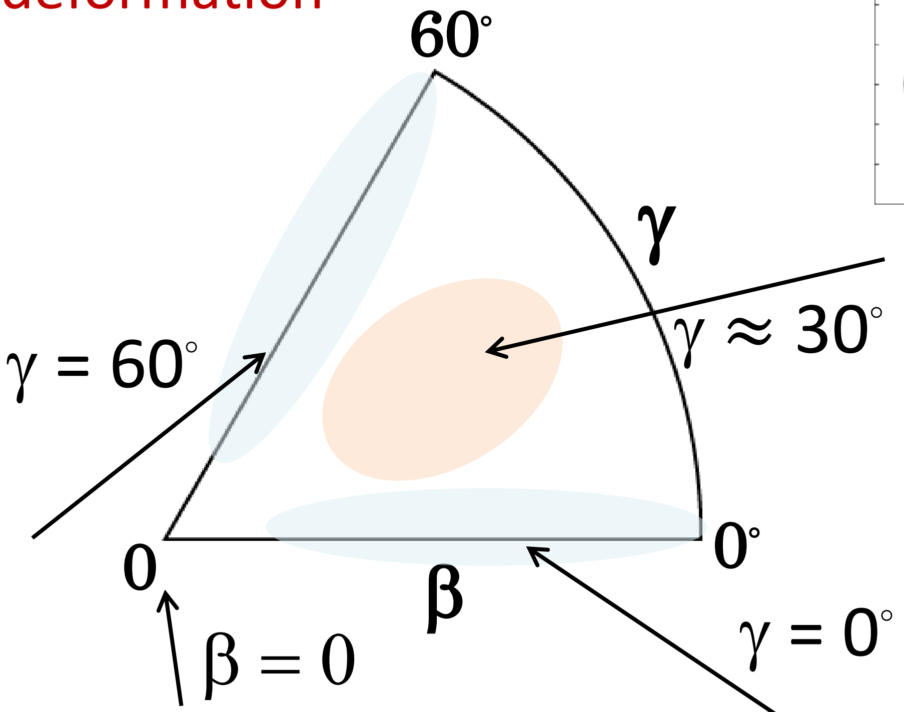
● Nuclear quadruple deformation (β,γ)

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

^{12}C

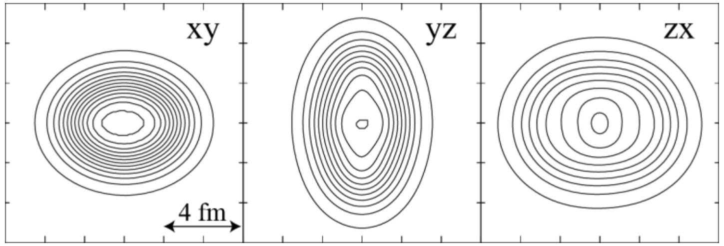


Oblate deformation
short axis symmetry



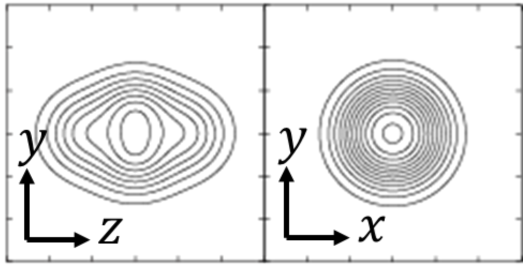
Spherical

^{26}Mg



Triaxial deformation
no symmetry axis

^{20}Ne



Prolate deformation
long axis symmetry

変形の変化は？
Λ粒子を加えたときの変形による違いは？

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
ΛN : YNG interaction

◆Wave function

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

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

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

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

- **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. :**

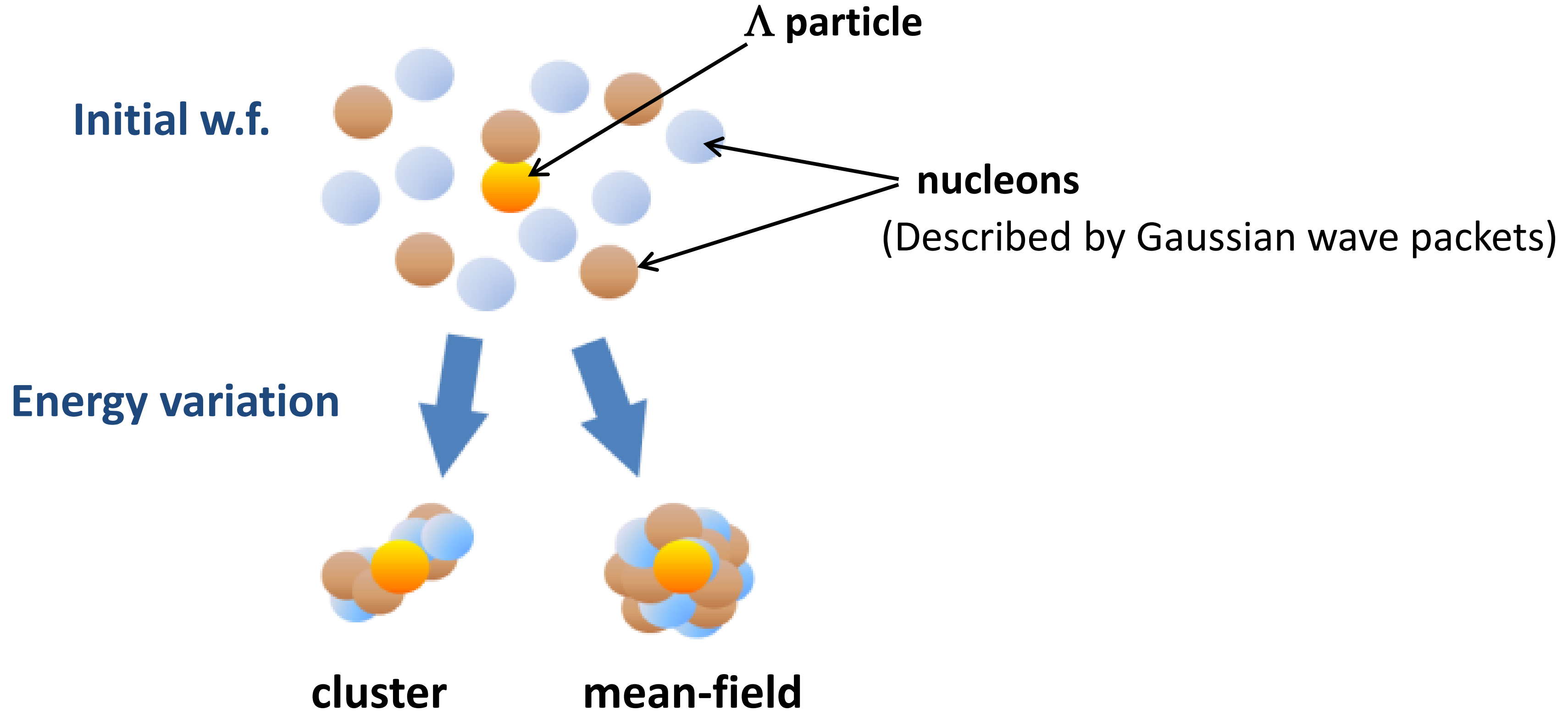
$$\psi(\vec{r}) = \sum_m c_m \varphi_m(r_\Lambda) \otimes \frac{1}{\sqrt{A!}} \det[\varphi_i(\vec{r}_j)]$$

Theoretical framework: HyperAMD

◆Procedure of the calculation

Variation

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



Theoretical framework: HyperAMD

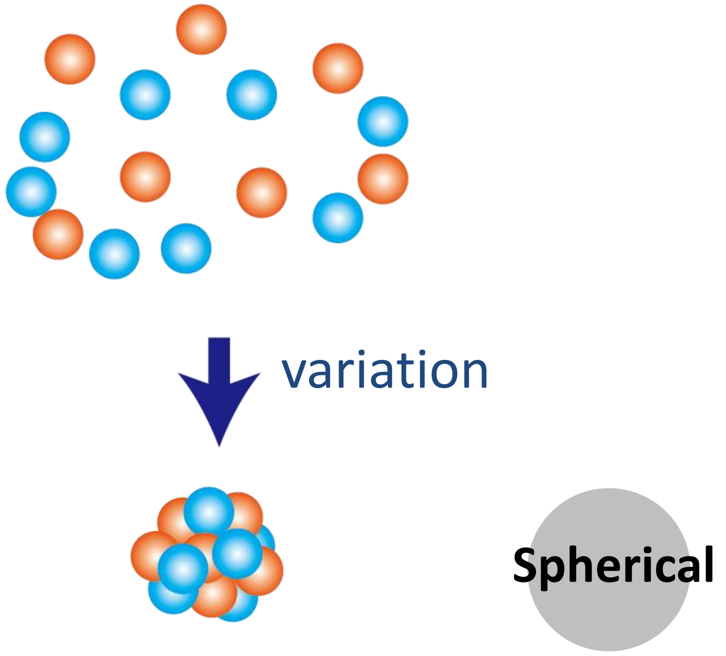
◆Procedure of the calculation

- **Energy variation with constraint on nuclear quadrupole deformation**

Described by (β, γ)

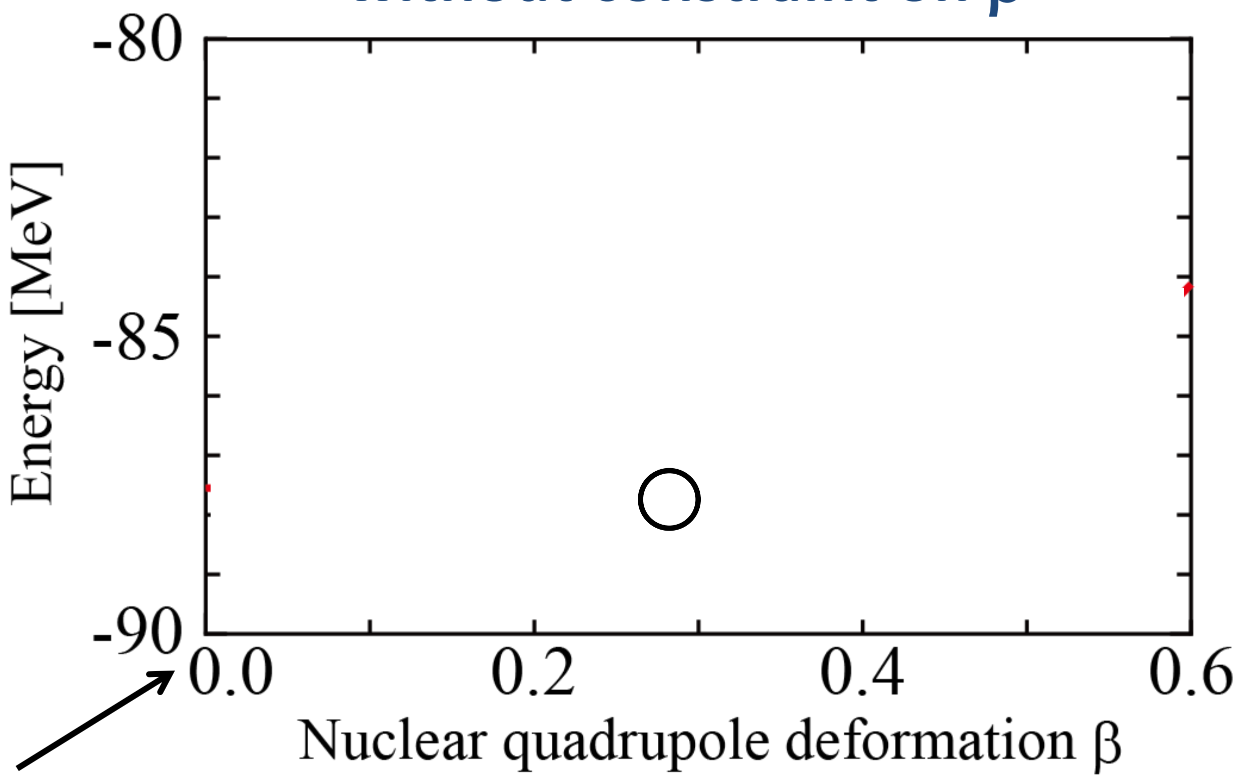
e.g.) ^{12}C

Initial w.f.



β = 0.00

without constraint on β



Theoretical framework: HyperAMD

◆Procedure of the calculation

- **Energy variation with constraint on nuclear quadrupole deformation**

Described by (β, γ)

e.g.) ^{12}C

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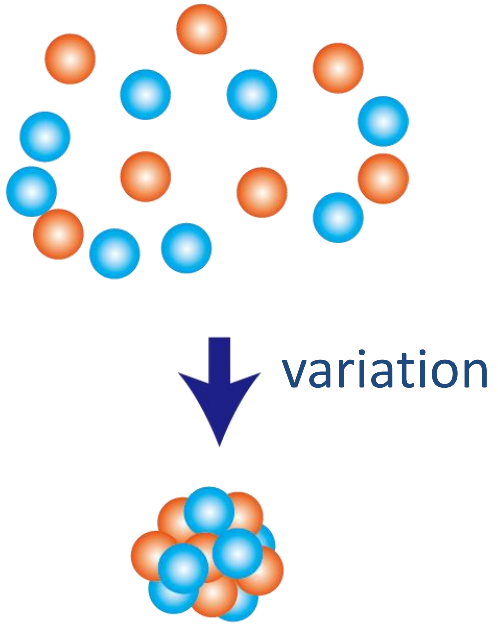
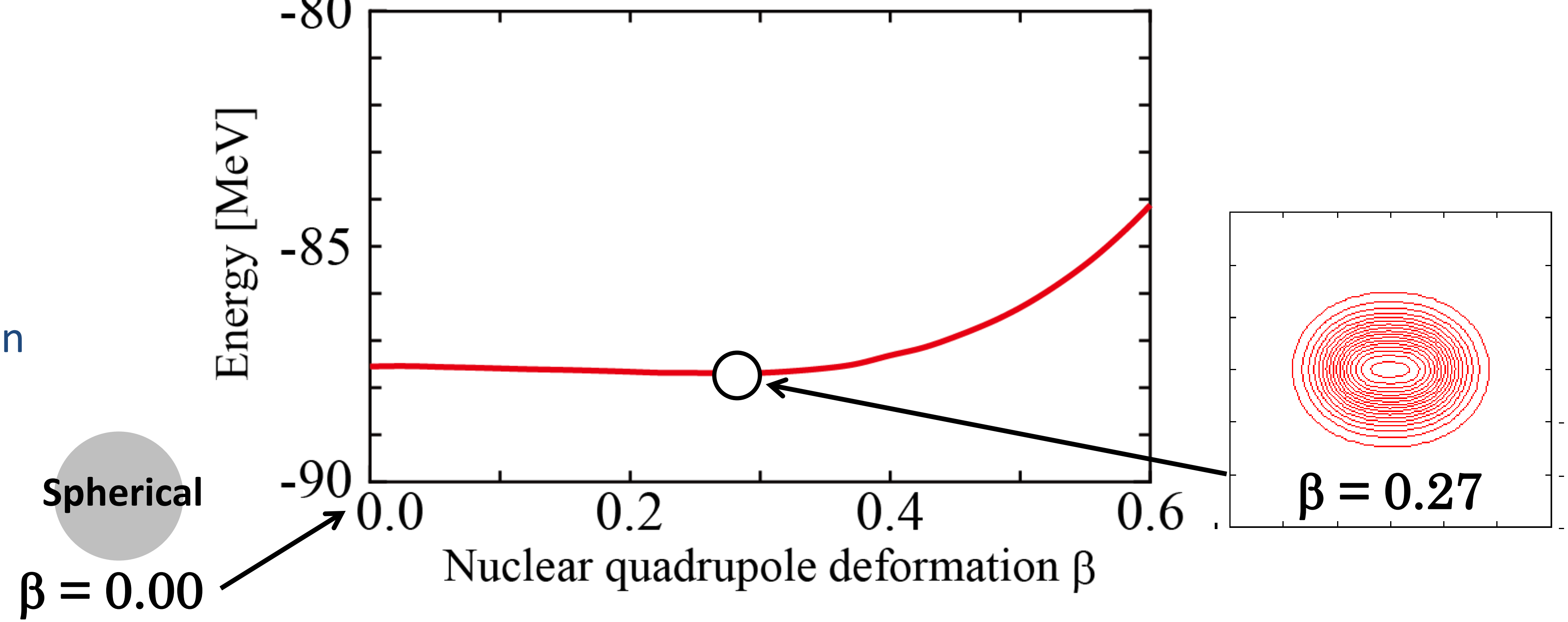
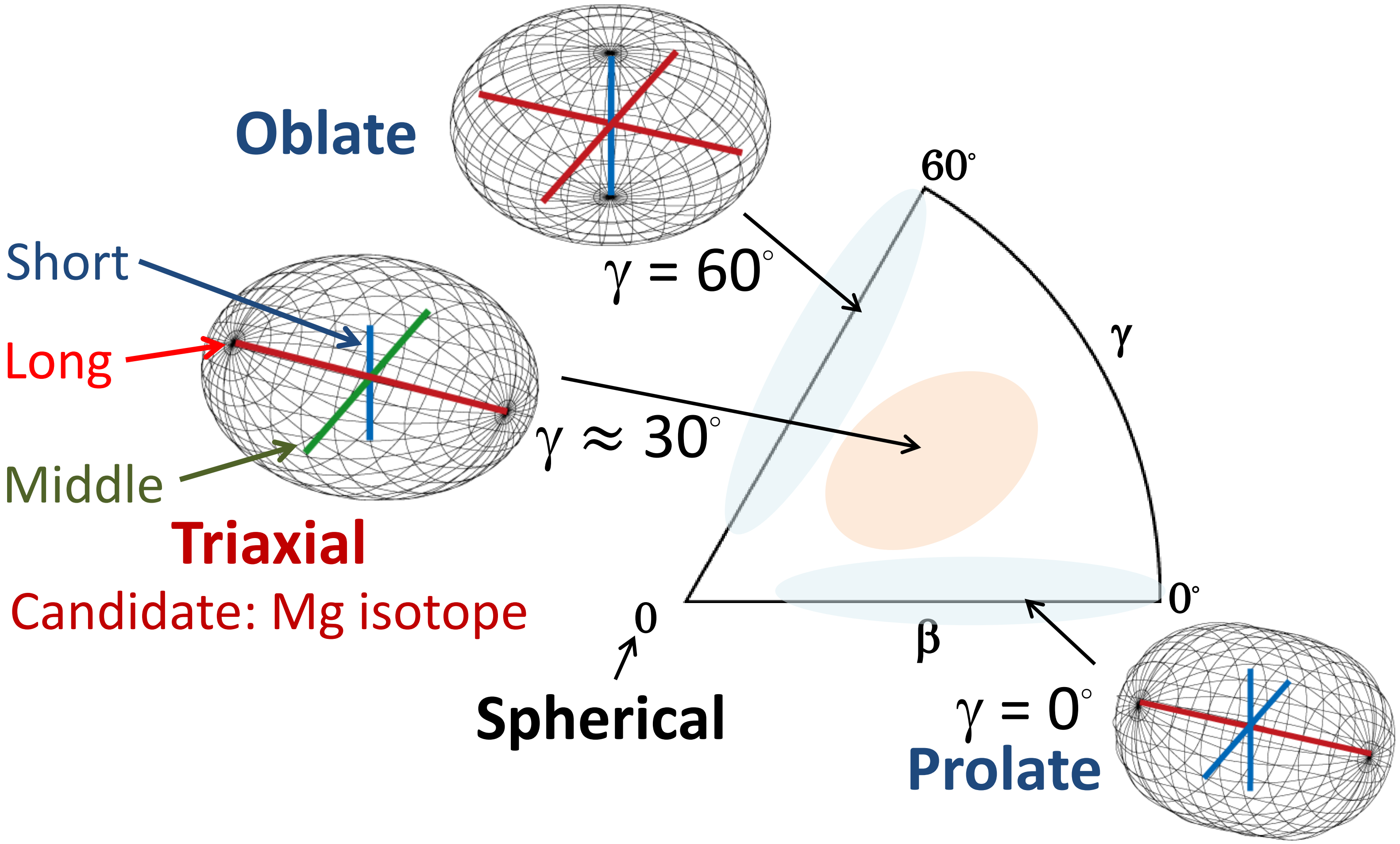
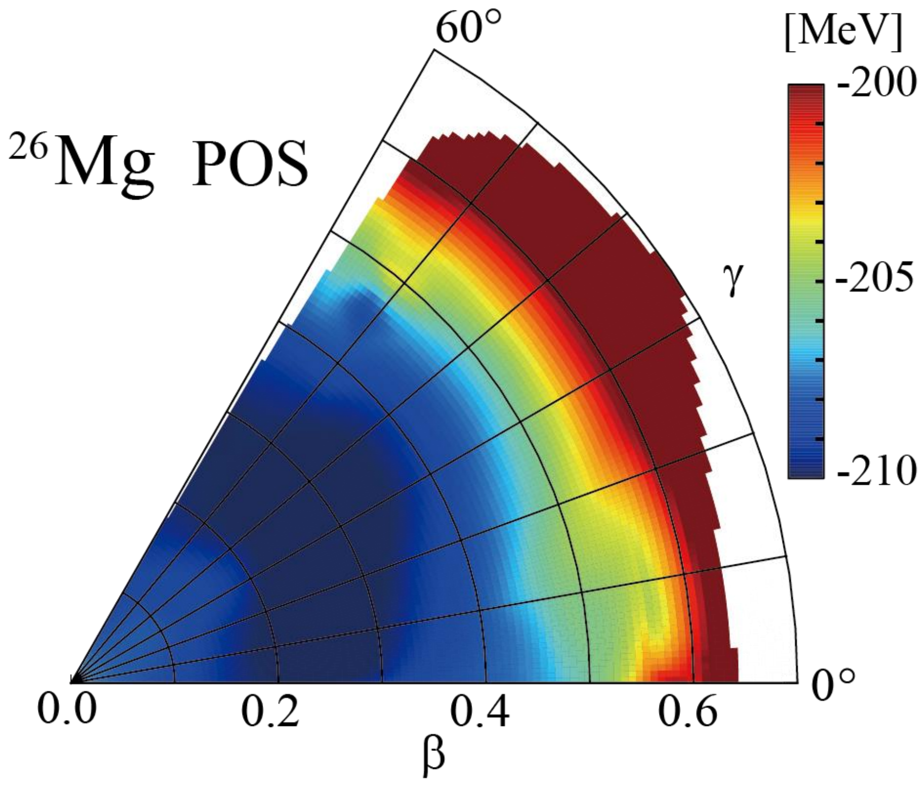


with constraint on β



Quadrupole deformation (β, γ)





- Energy variation is performed at each (β, γ)
- *p* states are obtained by constraint on Λ single particle wf: $V_f = \lambda \sum_f |\varphi_f\rangle\langle\varphi_f|$

Theoretical Framework: HyperAMD

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

◆Procedure of the numerical calculation

Variation

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

↓

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 $N^{J\pm}_{sK,s'K'}$

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

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

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

Theoretical Framework: HyperAMD

◆AMD(HyperAMD)の利点

- クラスター構造も平均場構造も記述できる
- 核構造の動的変化を記述可能
- 変形の軸対称性を仮定しない
- 偶偶核・奇奇核・偶奇核いずれも可

◆適用範囲

- 質量数が大きすぎると適用できない（A=59までは適用例あり）
- 模型計算：bareな核力ではなく、有効核力（バリオン間力）が必要

Recent development based on AMD

To describe short-range & tensor correlations with bare nuclear force

- **TOAMD: adding correlation functions multiplying AMD wf**

  T. Myo, H. Toki, K. Ikeda, H. Horiuchi, T. Suhara, PTEP**2015**,073D02

- **HMAMD: high-momentum components is included in AMD wf**

  T. Myo, H. Toki, K. Ikeda, H. Horiuchi, T. Suhara, M. Lyu, M. Isaka, T. Yamada, PTEP**2017**, 111D01 (2017)

Example: applications of HMAMD to ^{3}H

AMD wf.

$$\Phi_{\rm AMD} = \frac{1}{\sqrt{A!}} \det\left\{\Pi_{i=1}^{A} \varphi_i(\vec{r}_i)\right\},$$

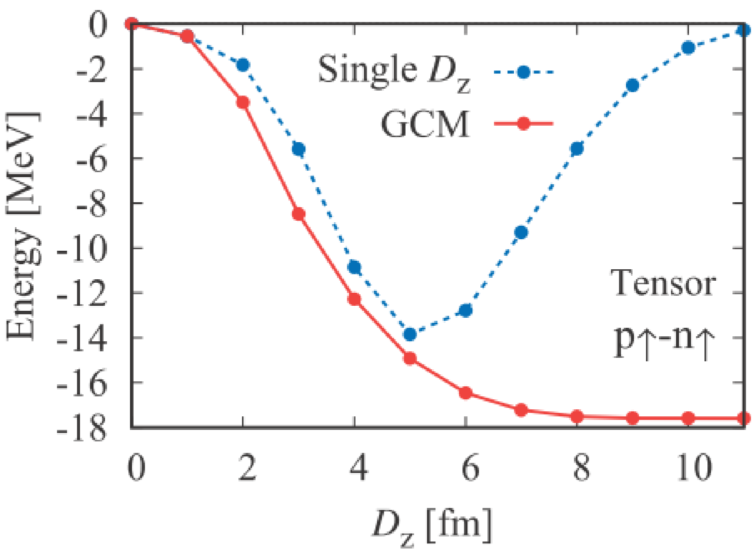
$$\varphi(\vec{r}\,) = \phi(\vec{r}\,)\chi_\sigma \chi_\tau ,$$

$$\phi(\vec{r}\,) = \exp\{-\nu(\vec{r} - \vec{Z})^2\},$$

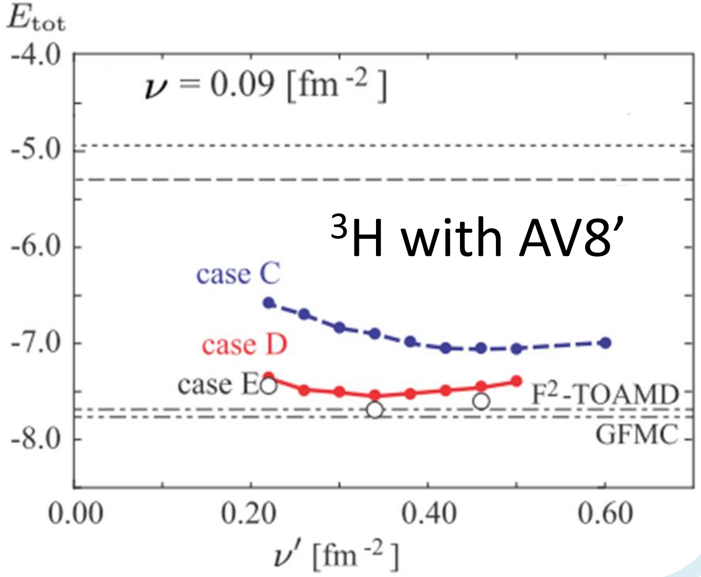
Imp. relation: $\frac{\langle\phi|\vec{p}\,|\phi\rangle}{\langle\phi|\phi\rangle} = 2\nu {\rm Im}(\vec{Z}),$

HM-pair: $\vec{Z}_1 = i\vec{D}, \quad \vec{Z}_2 = -i\vec{D}$

Myo, et al., PTEP**2017**, 111D01 (2017)



Isaka, et al., PRC**106**,044310(2022)



Λハイパー核の構造として期待できること

- **glue-like role: Λ粒子により、非束縛状態が束縛する**
- **構造の動的変化：変形の変化、核半径の収縮**
- **変形・構造の違いに対するエネルギー（B_Λ）の違い**
- **Λ粒子が変形状態に結合することで現れる新奇な状態**

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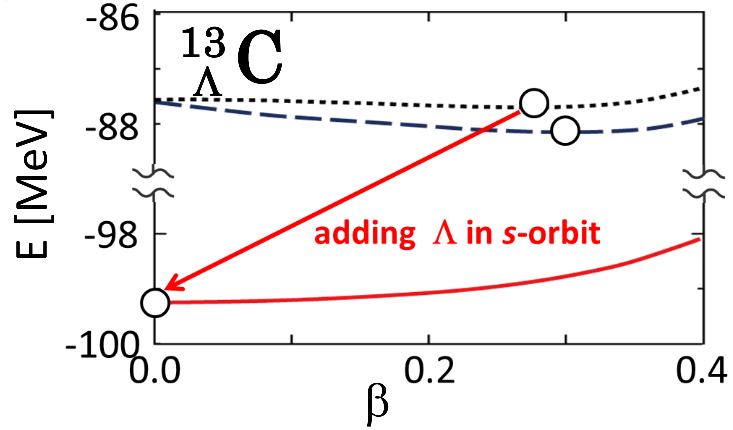
Deformation change by Λ particle

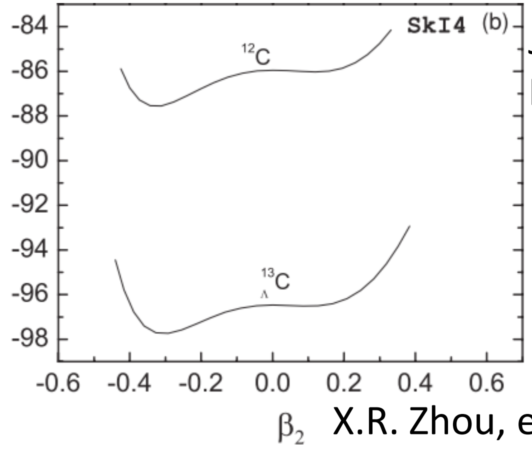
Many authors predict that Λ in *s*-orbit reduces nuclear deformation

Antisymmetrized molecular Dynamics (AMD)

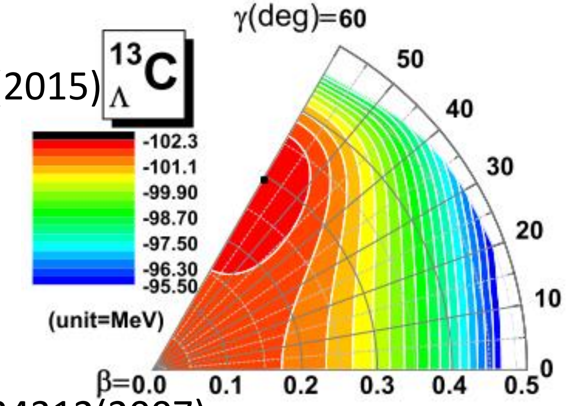
M.I, et al., PRC**83**, 044323(2011)



Skyrme-Hartree-Fock (SHF)



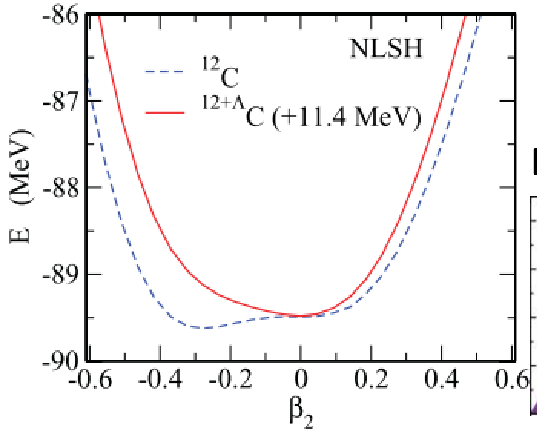
J.W. Cui, et al, PRC**91**,054306(2015)



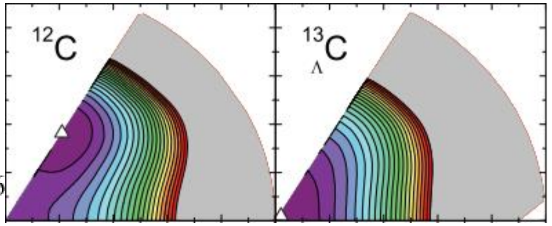
X.R. Zhou, et al., PRC**76**, 034312(2007)

Relativistic mean-field (RMF)

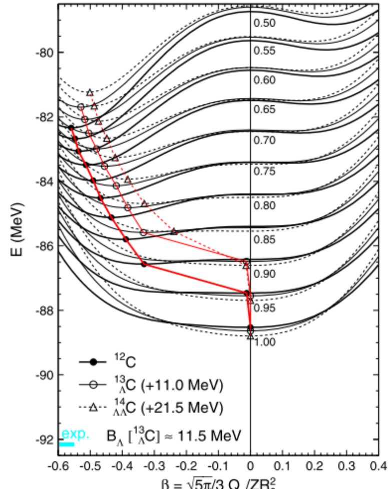
Win and Hagino, PR C**78**, 054311(2008)



B.N. Lu, et al., PRC**84**, 014328 (2011)



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, PRC**91**, 064305(2015); **97**, 064318(2018)

… and so on

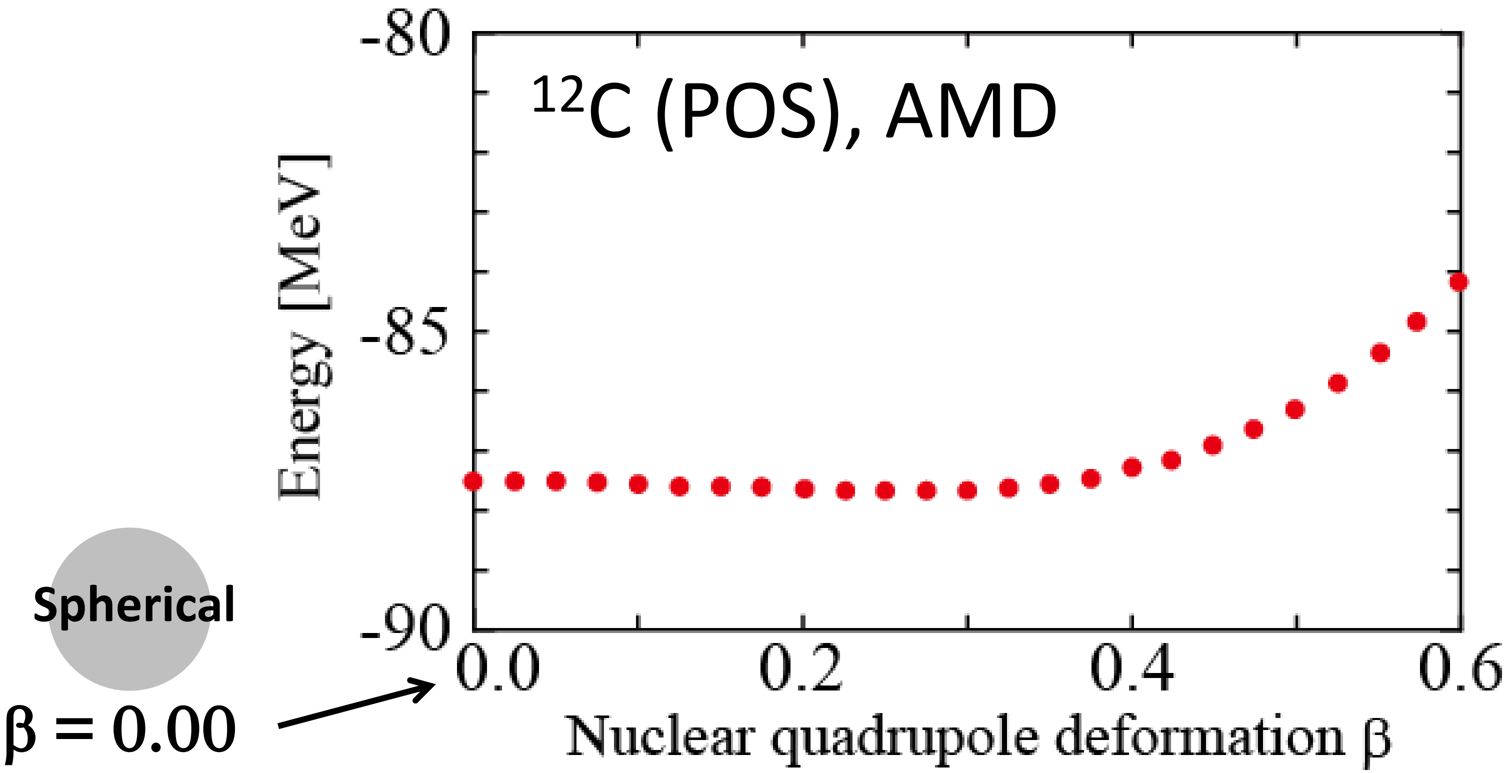
Deformation change by Λ particle

◆How to analyze from energy surface

Example: ^{12}C with AMD(antisymmetrized molecular dynamics)

- Energy variation at each β (and γ) ⟶ energy curve as a function of β
- Energy minimum at (β,γ)

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



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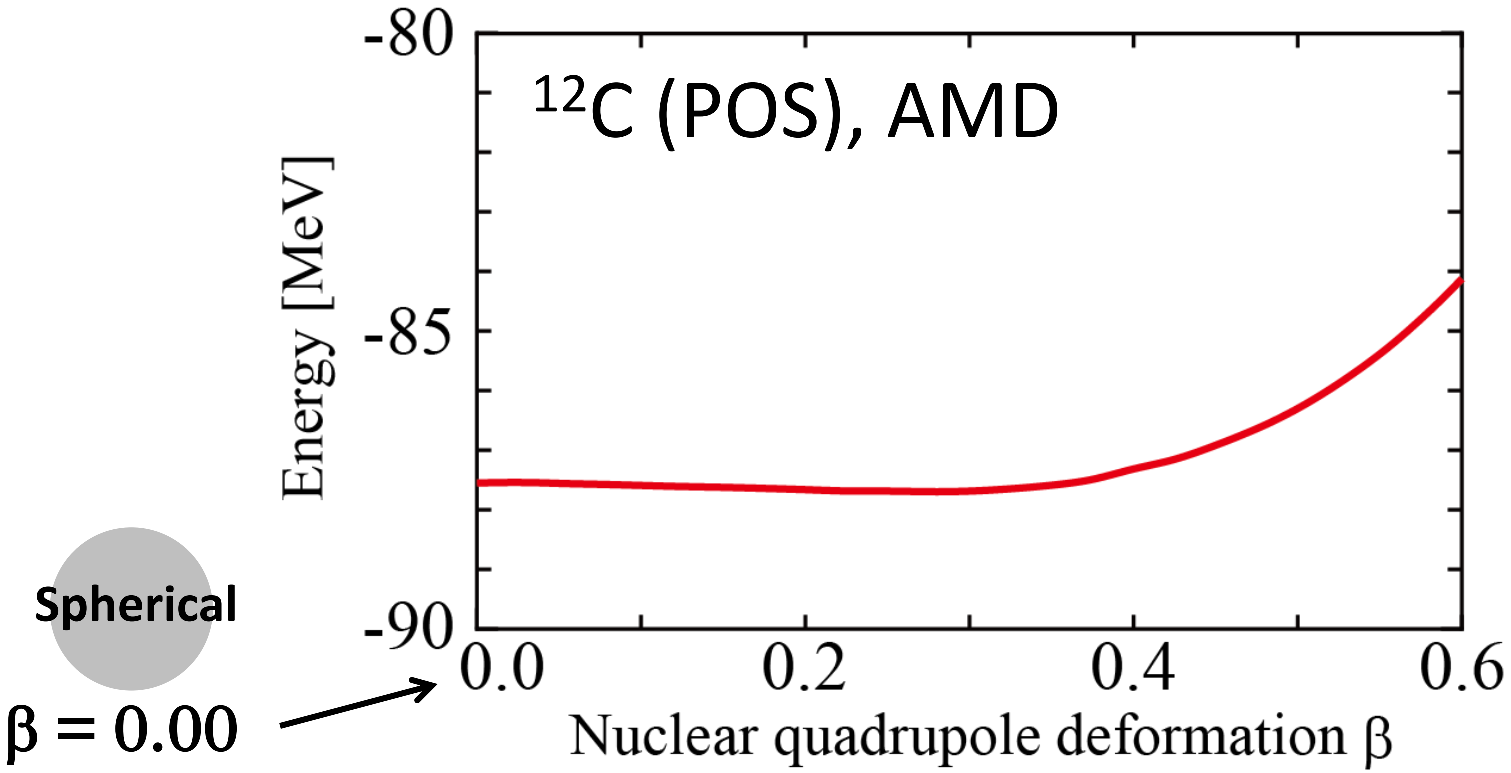

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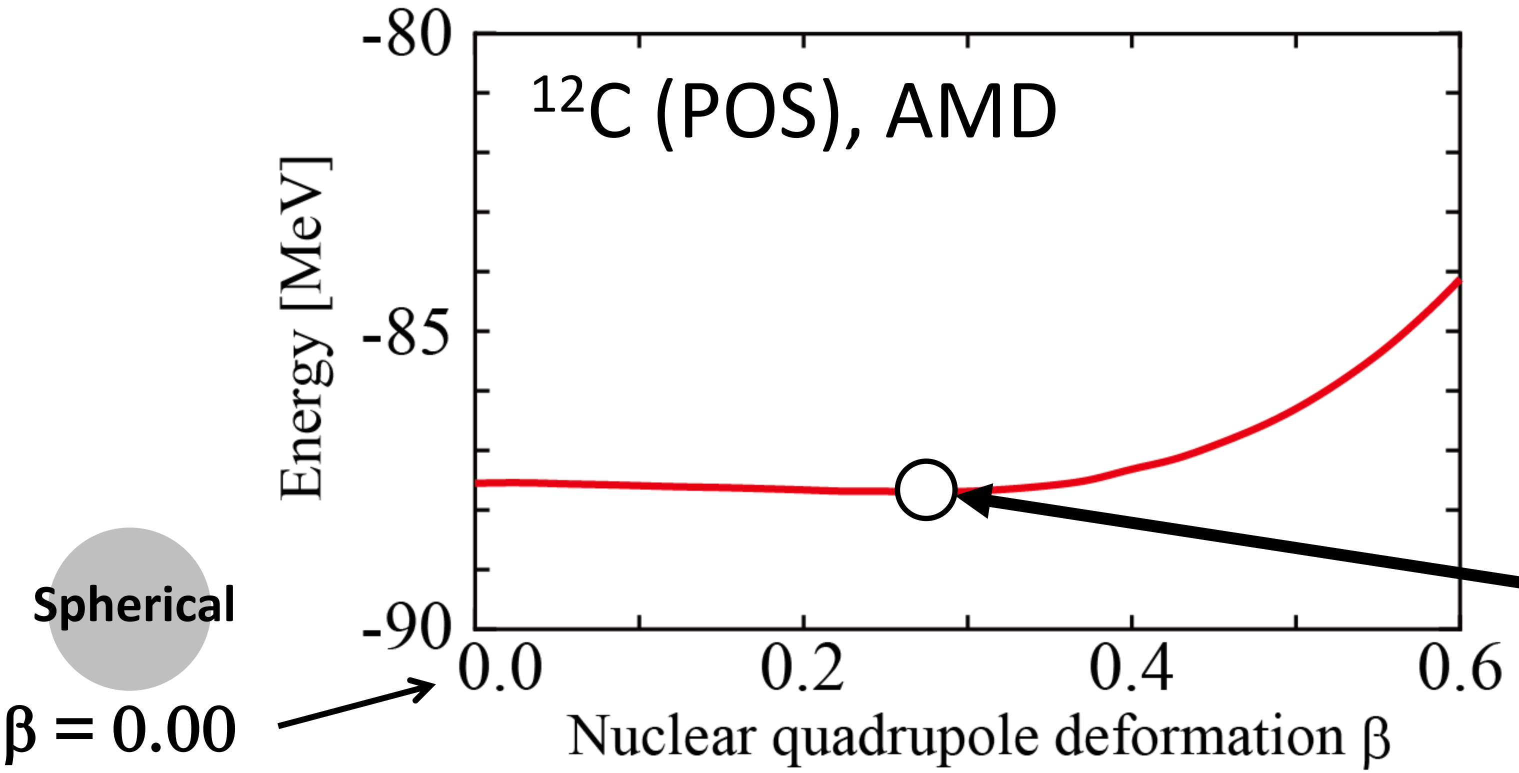
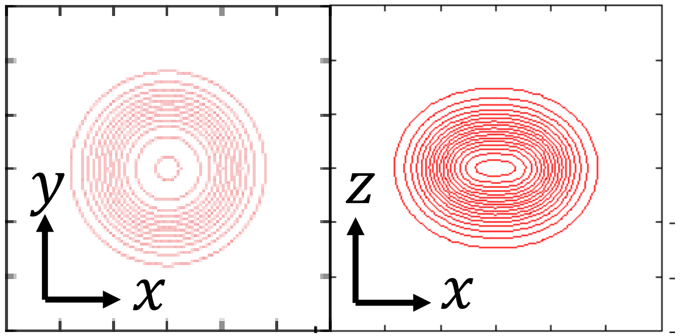


Energy minimum



β = 0.27, γ = 60°

Deformation change by Λ in *s*-orbit

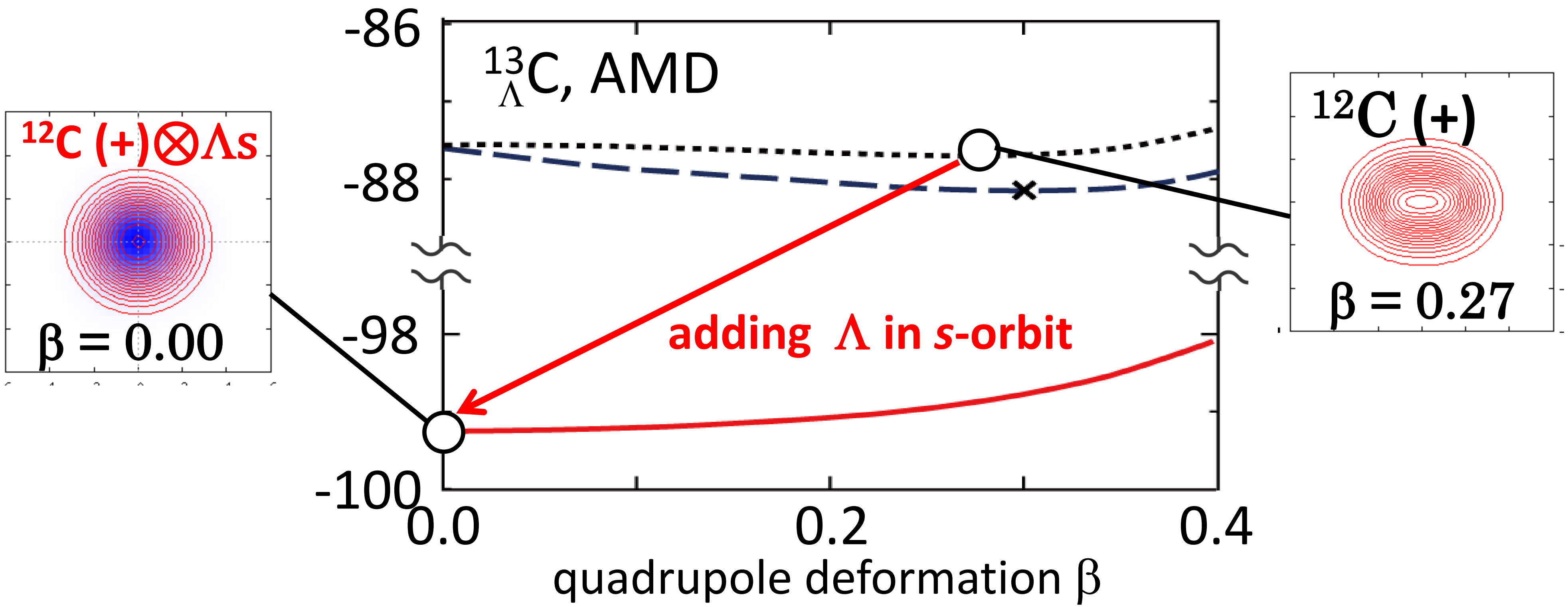
◆How to analyze from energy surface

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

Example: ^{12}C with AMD(antisymmetrized molecular dynamics)

- Energy variation of hypernucleus

→ energy minimum moves to smaller β with Λ in *s*-orbit

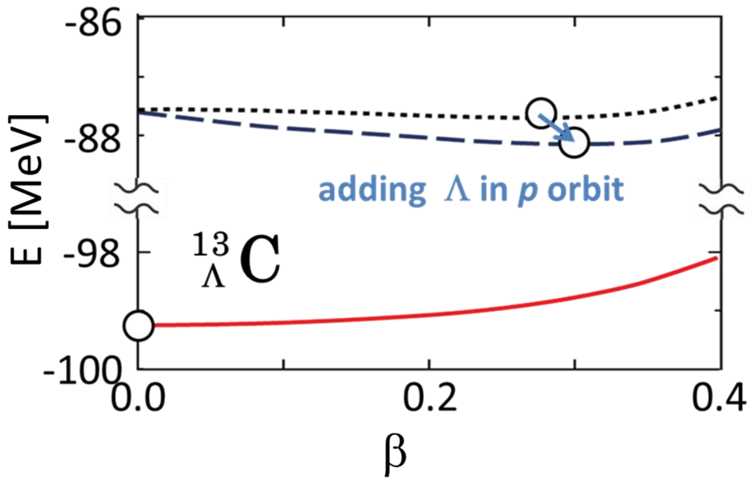


Deformation change by Λ particle

Λ in *p*-orbit enhances nuclear deformation

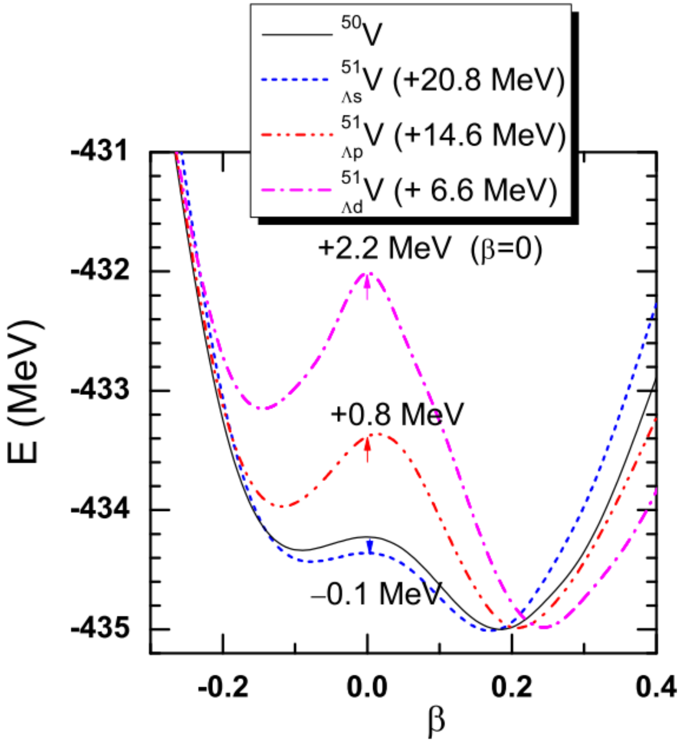
Antisymmetrized molecular dynamics (AMD)

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



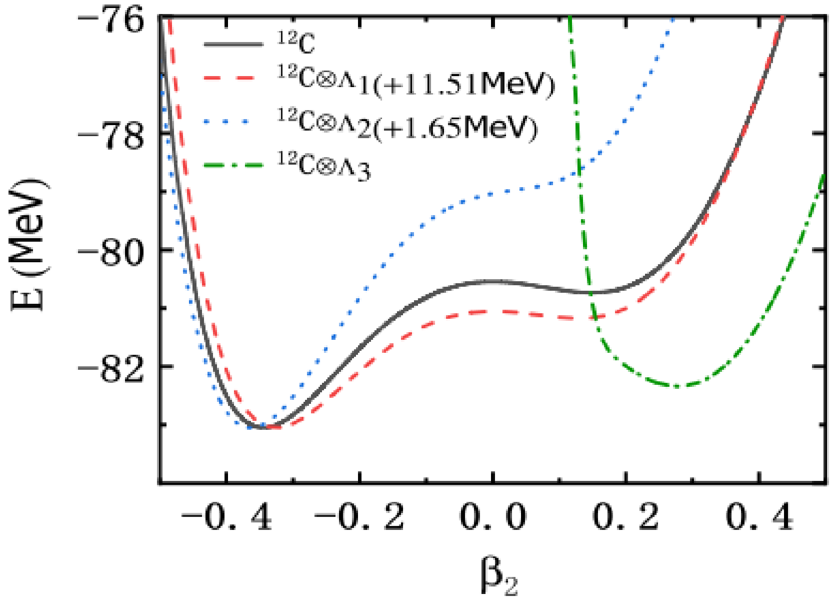
Triaxially deformed relativistic mean-field

W. X. Xue, et al., PRC**91**, 024327(2015)



Deformed Skyrme-Hartree-Fock (DSHF)

Bi-Cheng Fang et al., EPJA**56**,11(2020)

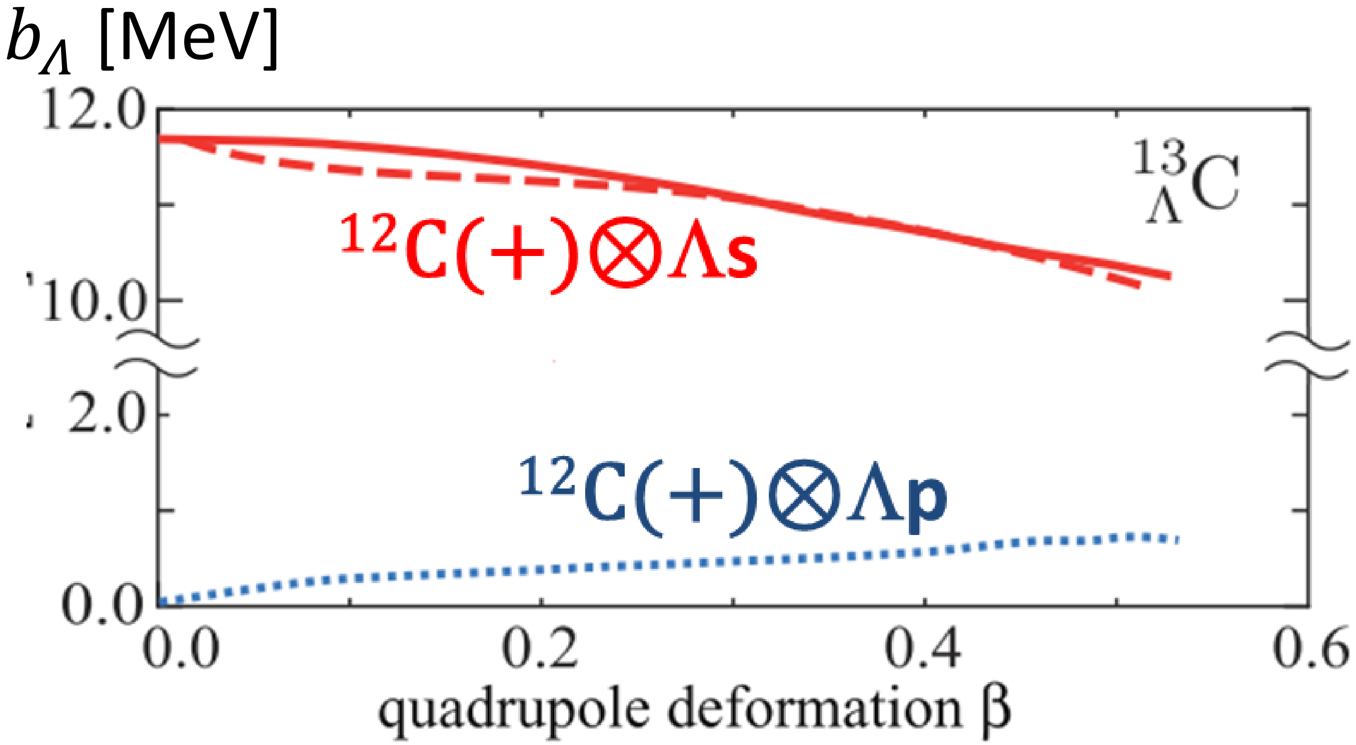


Deformation change of Λ in higher orbits such as *d*-orbit is also predicted by several papers:
W. X. Xue, et al., PRC**91**, 024327(2015), X. Y. Wu, et al., PRC**95**, 034309(2017)

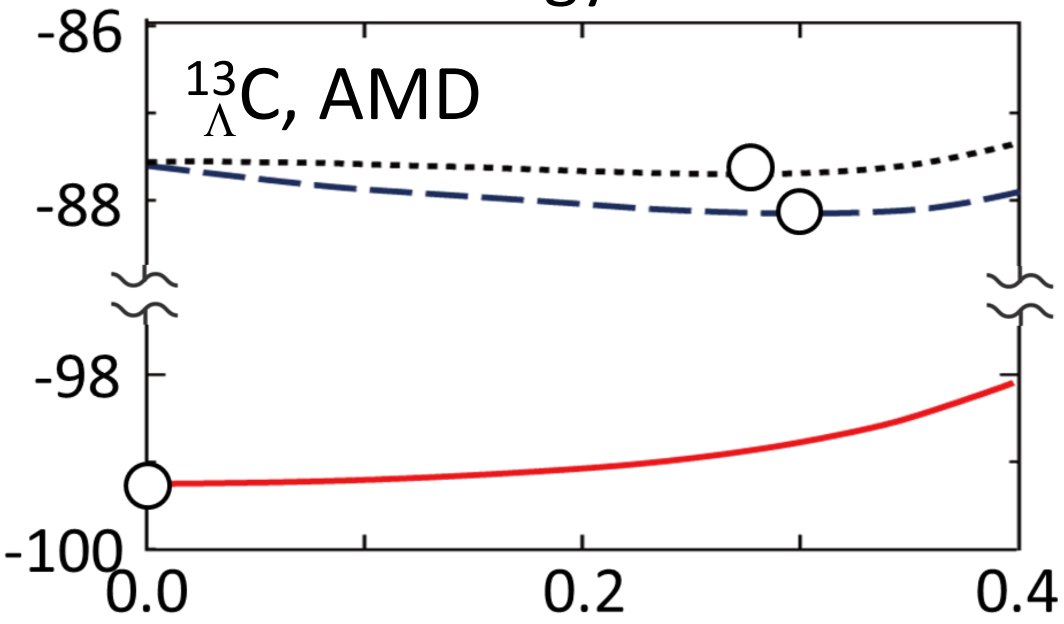
Why does Λ change nuclear deformation?

- Λ in *s* orbit is deeply bound at small β, while Λ in *p* orbit prefers deformation
- Competition b/w Λ binding energy and energy surface of core nucleus

Λ binding energy: $b_\Lambda(\beta) = E_{core}(\beta) - E_\Lambda(\beta)$



cf. energy curve

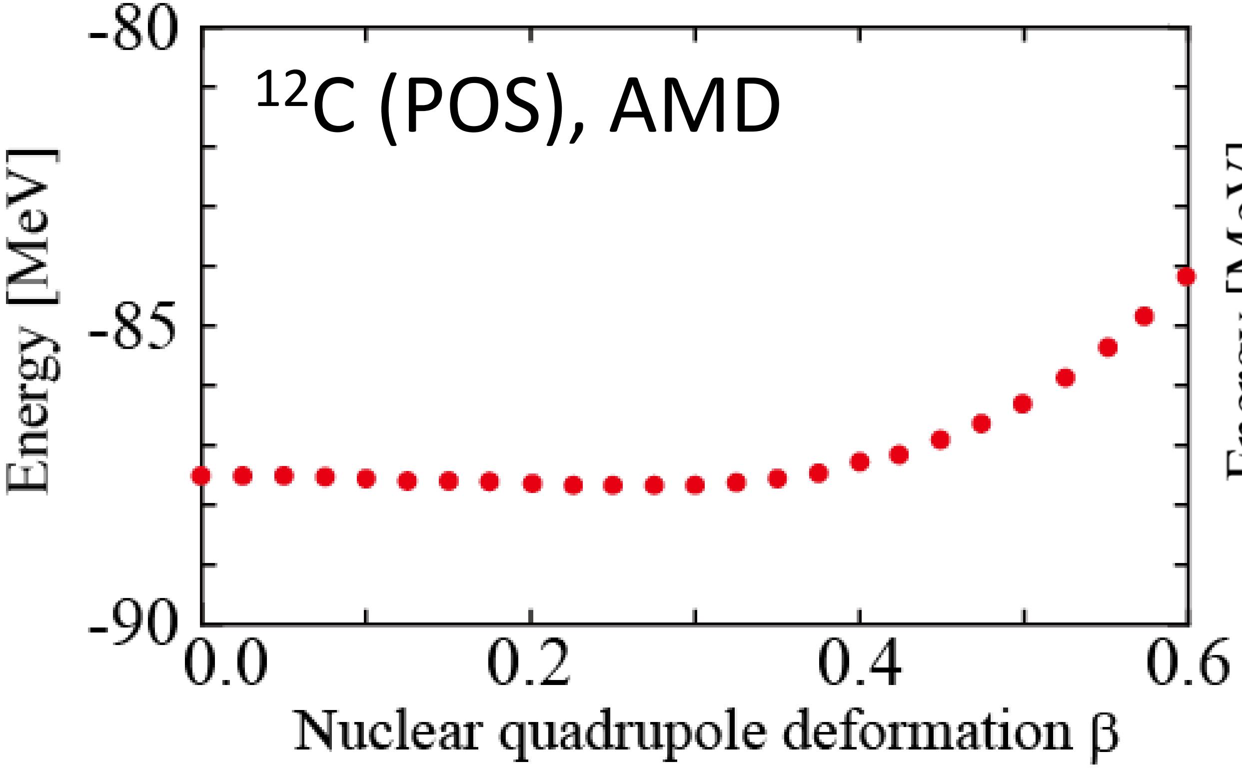


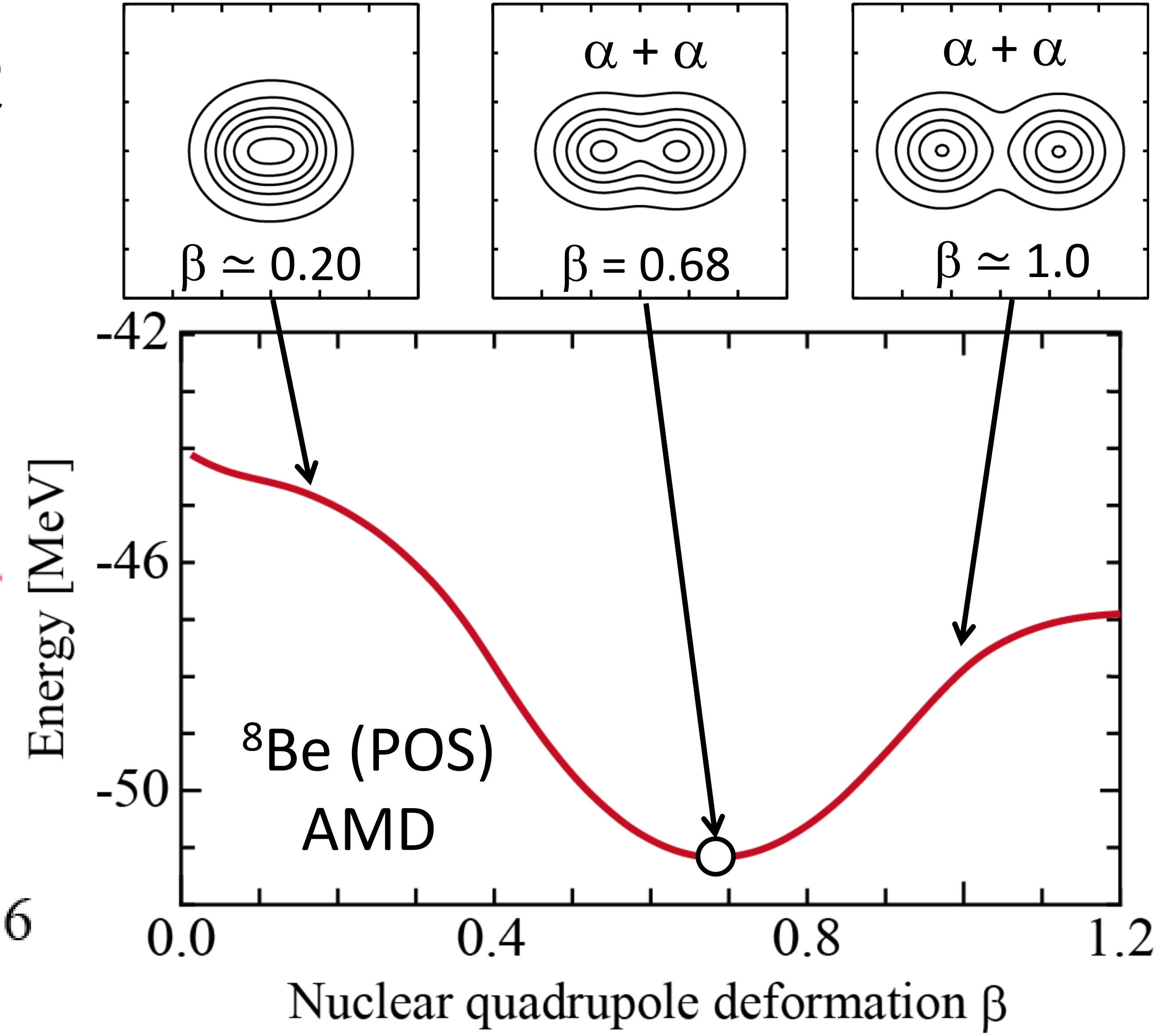
M.I, et al., PRC**83**, 044323(2011)

"binding energy of Λ" vs. "energy surface of the core nuclei"

Energy surface of core nuclei

Energy surface (energy curve)は
核構造を反映している

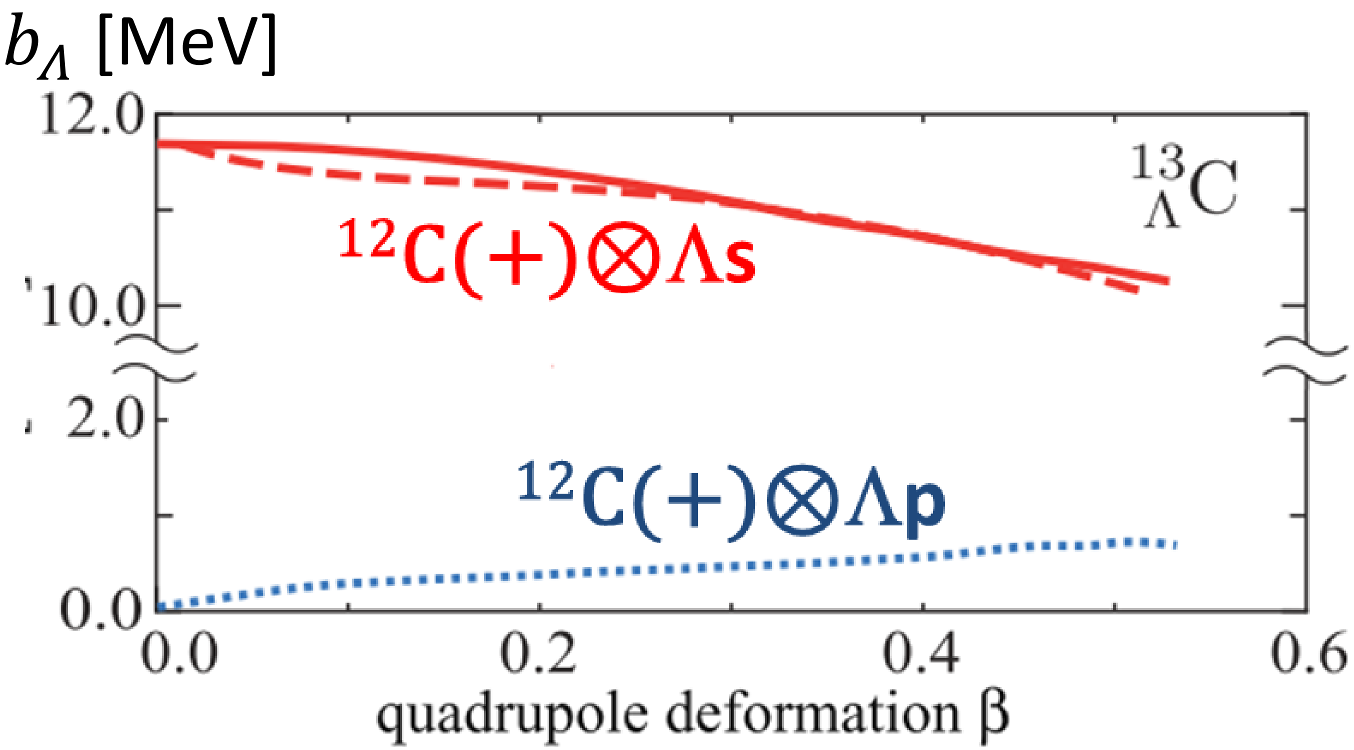


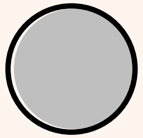
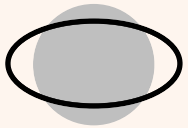


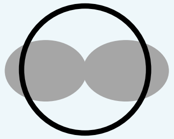
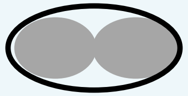
Deformation change by Λ particle

"*Overlap between Λ and N*" is the key!

Λ in *s*-orbit (*p*-orbit) is deeply bound with smaller β (larger β) due to larger overlap between Λ and nucleons



Λ in *s* orbit	 **Small β**	 **Large β**
Overlap b/w Λ & N	**Large**	**Small**
ΛN attraction	**Large**	**Small**

Λ in *p* orbit	 **Small β**	 **Large β**
Overlap b/w Λ & N	**Small**	**Large**
ΛN attraction	**Small**	**Large**

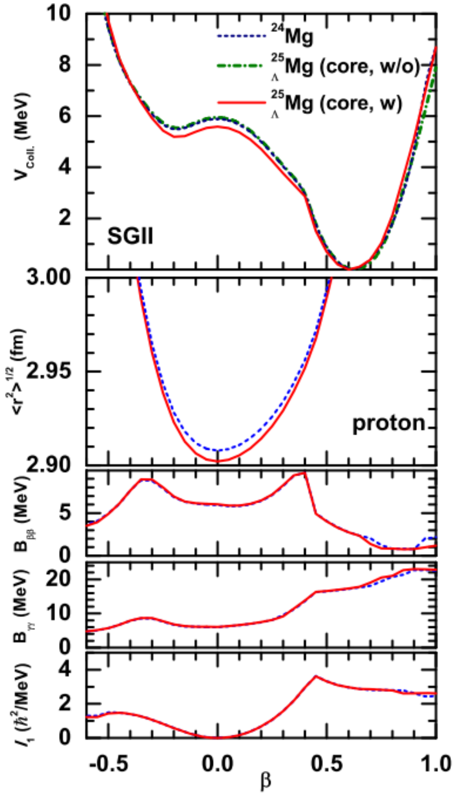
M.I, et al., PRC**83**, 044323(2011)

Deformation change by Λ particle

◆Deformation changes on (β, γ) plane: triaxiality

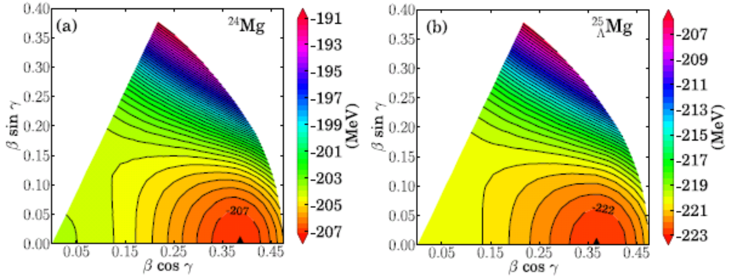
non-relativistic energy density functional theory

J.M. Yao, et al, NPA**868** (2011)

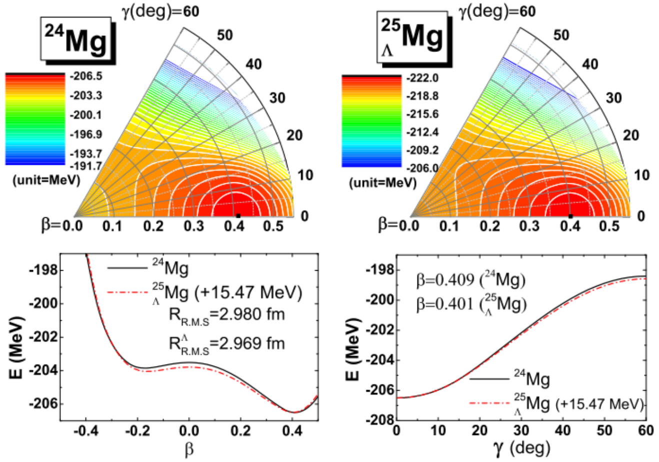


Skyrme-Hartree-Fock

Myaing Thi Win, et al., PRC**83** (2011)

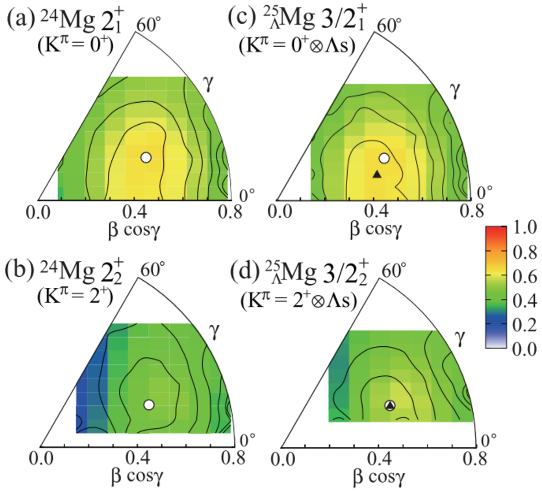


J.W. Cui, et al, PRC**91** (2015)



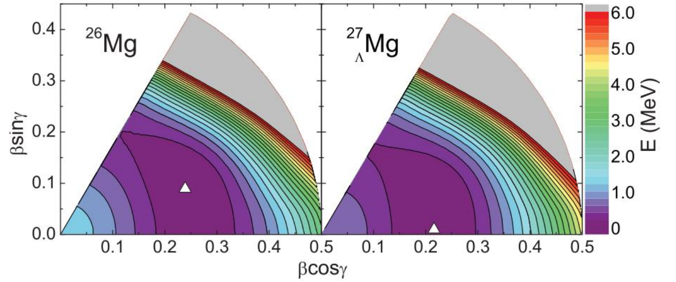
AMD

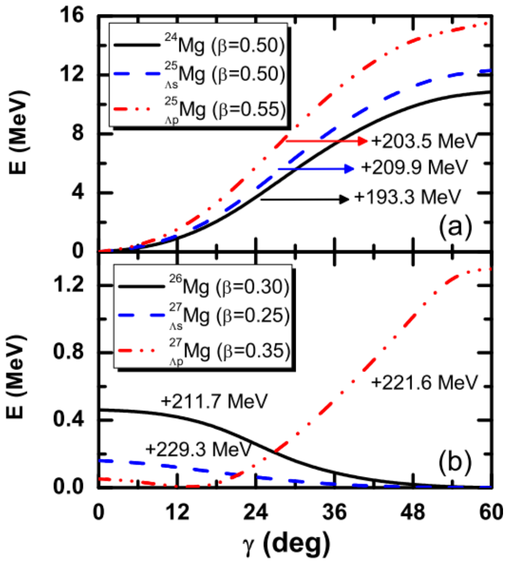
M.I, et al., PRC**85** (2012)



Relativistic mean-field

B.N. Lu, et al., PRC**84** (2011)





W. X. Xue, et al., PRC**91**(2015)

Changes of triaxially by Λ is also discussed by several authors

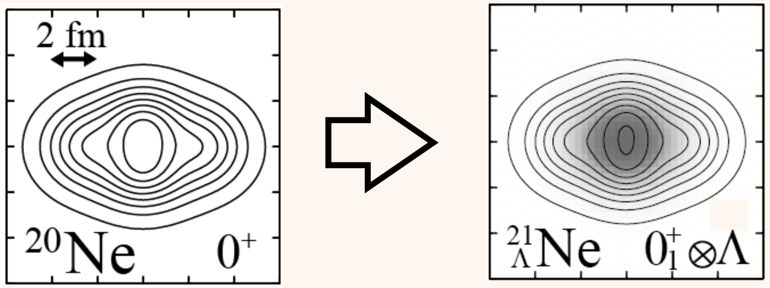
Structure dependence of “impurity effects”

◆ Example: $^{21}_{\Lambda}$Ne

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

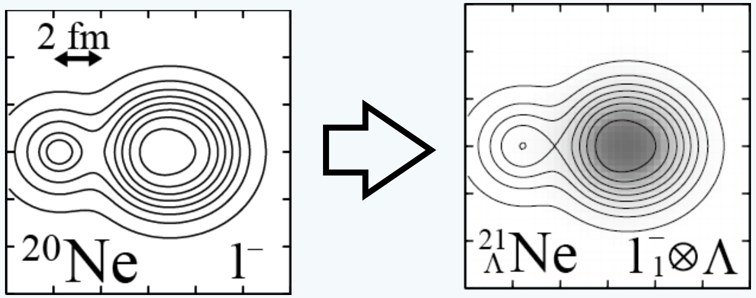
- **Shrinkage/deformation change are larger in α + ^{16}O + Λ cluster states, which appears as difference in intra-band B(E2) reduction**

Ground band



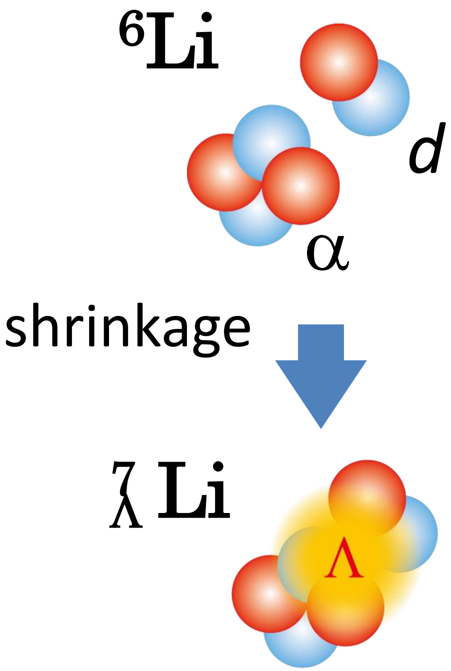
^{20}Ne $K^\pi=0^+$	r_{RMS}(fm)	$^{21}_{\Lambda}$Ne $0^+ \otimes \Lambda s$	r_{RMS}(fm)	Δr_{RMS}(fm)
0+	2.97	(1/2)+	2.92	−0.05
2+	2.96	(3/2)+	2.91	−0.05
		(5/2)+	2.91	−0.05
4+	2.93	(7/2)+	2.87	−0.06
		(9/2)+	2.88	−0.04
6+	2.87	(11/2)+	2.81	−0.05
		(13/2)+	2.83	−0.04

$K^\pi = 0^-$ (α + ^{16}O) band



^{20}Ne $K^\pi=0^-$	r_{RMS}(fm)	$^{21}_{\Lambda}$Ne $0^- \otimes \Lambda s$	r_{RMS}(fm)	Δr_{RMS}(fm)
1−	3.27	(1/2)−	3.15	−0.11
		(3/2)−	3.15	−0.11
3−	3.24	(5/2)−	3.13	−0.11
		(7/2)−	3.14	−0.10
5−	3.23	(9/2)−	3.11	−0.12
		(11/2)−	3.11	−0.13
7−	3.23	(13/2)−	3.06	−0.17
		(15/2)−	3.05	−0.18

cf. $^{7}_{\Lambda}$Li



Λハイパー核の構造として期待できること

- glue-like role: Λ粒子により、非束縛状態が束縛する
- 構造の動的変化：変形の変化、核半径の収縮
- 変形・構造の違いに対するエネルギー（B_{Λ}）の違い
- Λ粒子が変形状態に結合することで現れる新奇な状態

Difference of B_Λ depending on deformation

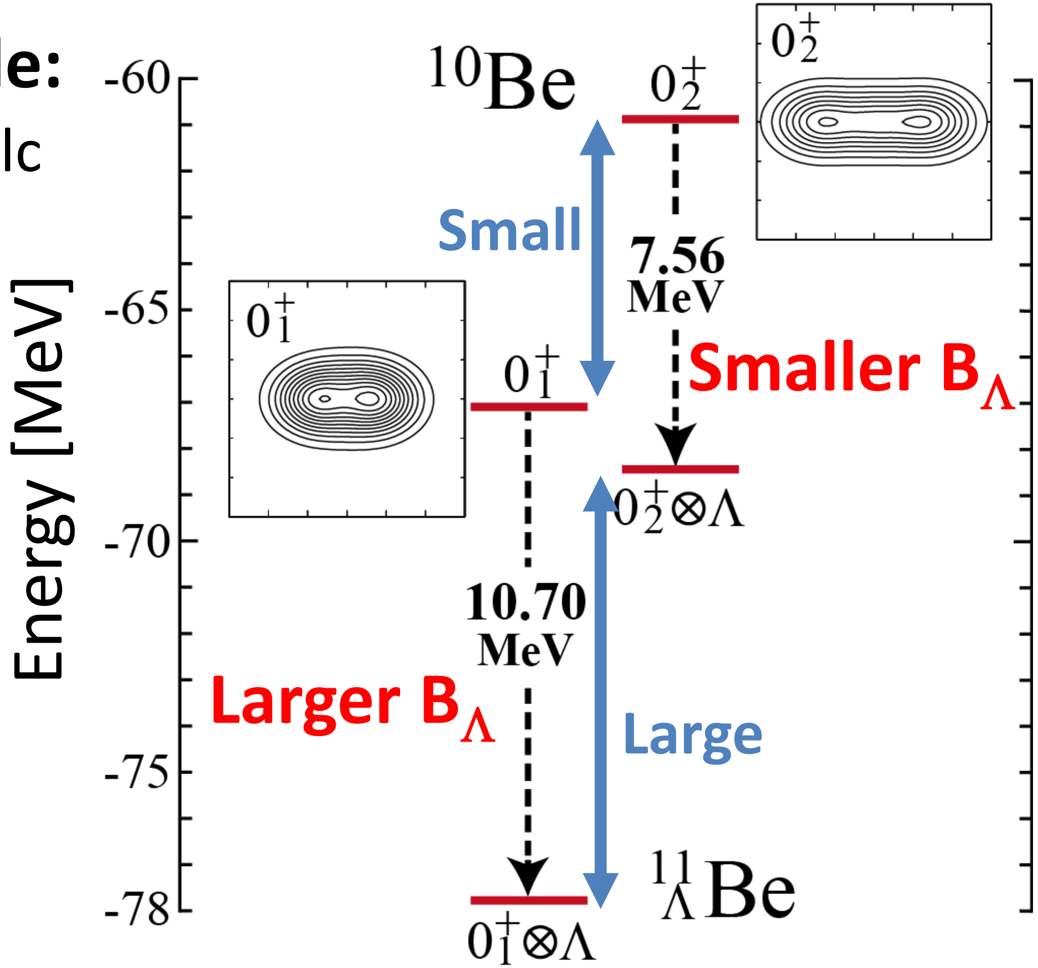
$^{11}_{\Lambda}$Be

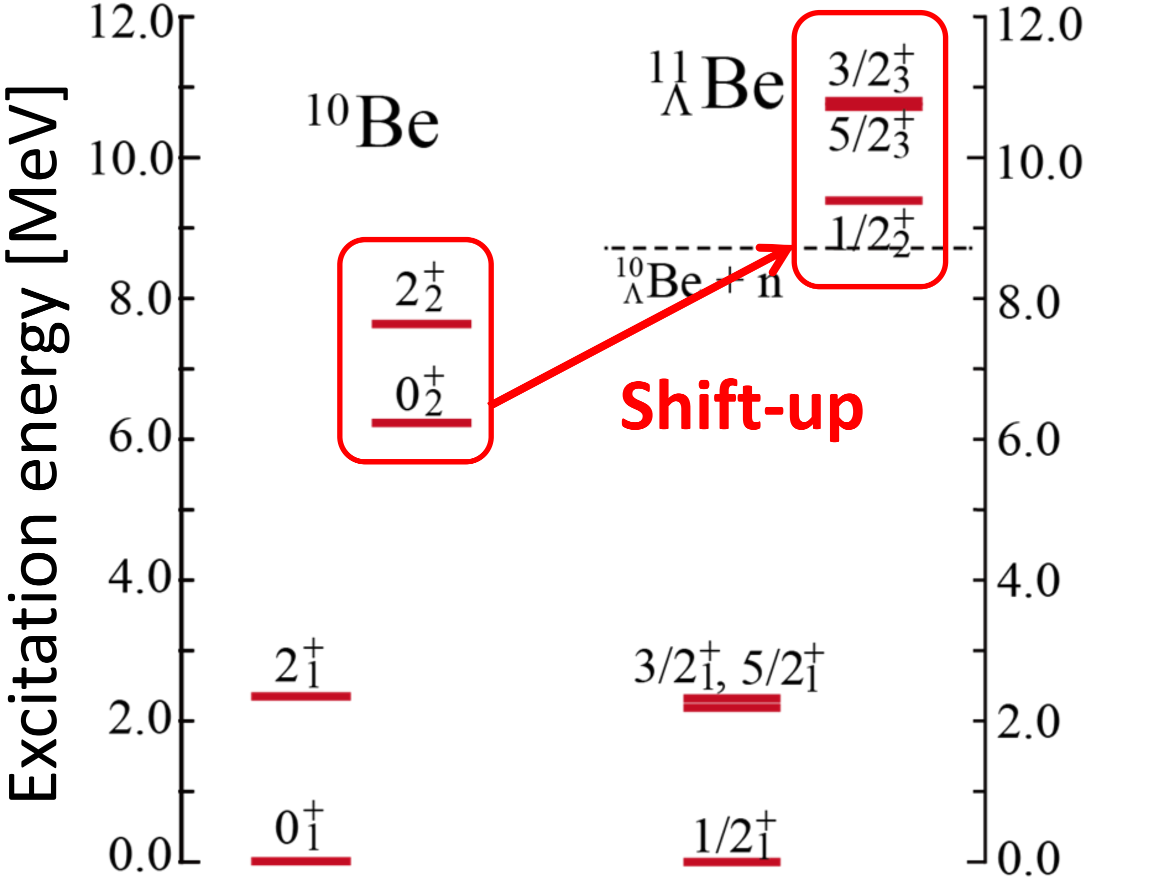
- Different deformations coexist near the ground state
- Λ in s orbit reduces it, but the difference remains
- B_Λ is different due to overlap → If different deformation coexist, shift-up/down in excitation spectra

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

Example:

AMD calc





Difference of B_Λ depending on deformation

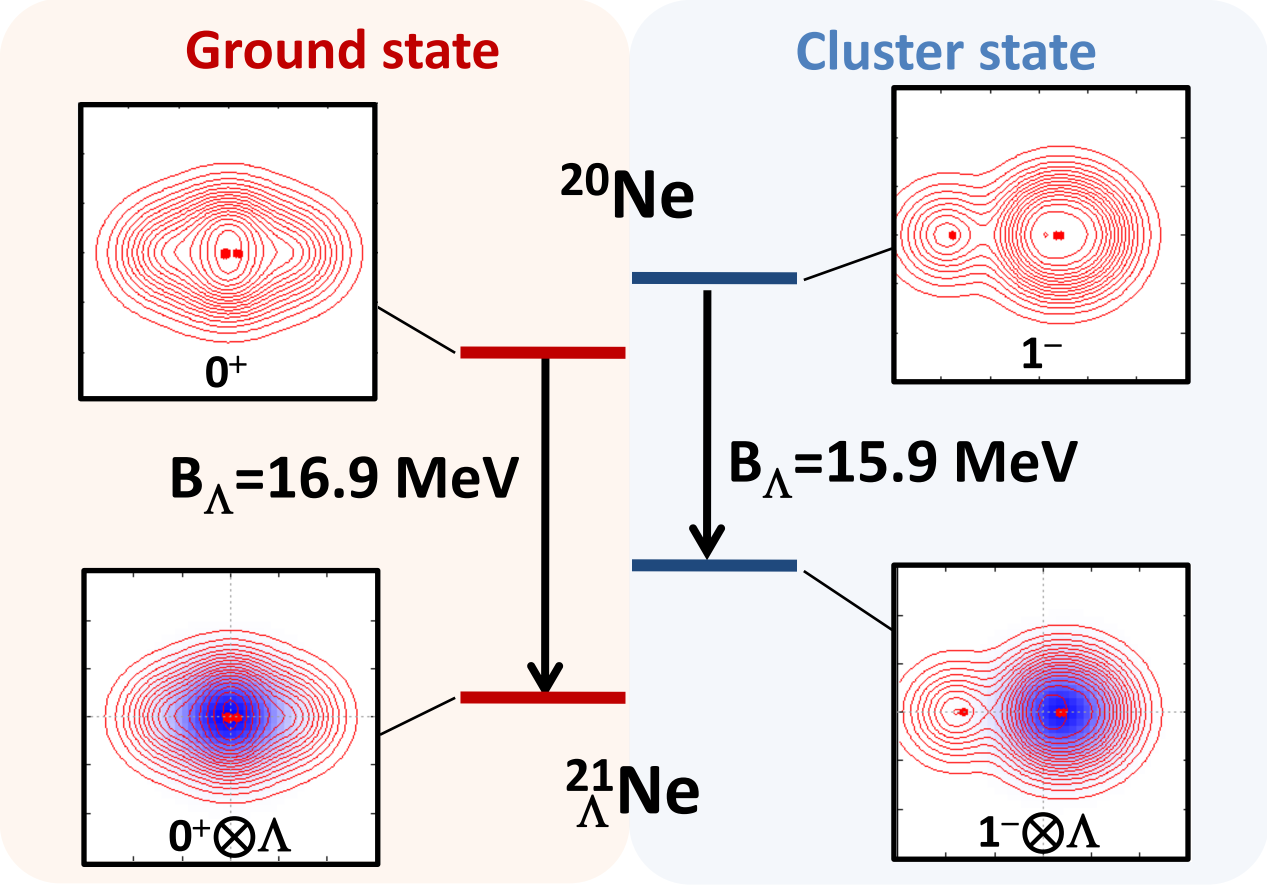
$^{21}_{\Lambda}Ne$

- Different structures coexist near the ground state
- Λ in s orbit changes them, but the difference remains
- Λ is localized around ^{16}O in α + ^{16}O + Λ state → difference of B_Λ

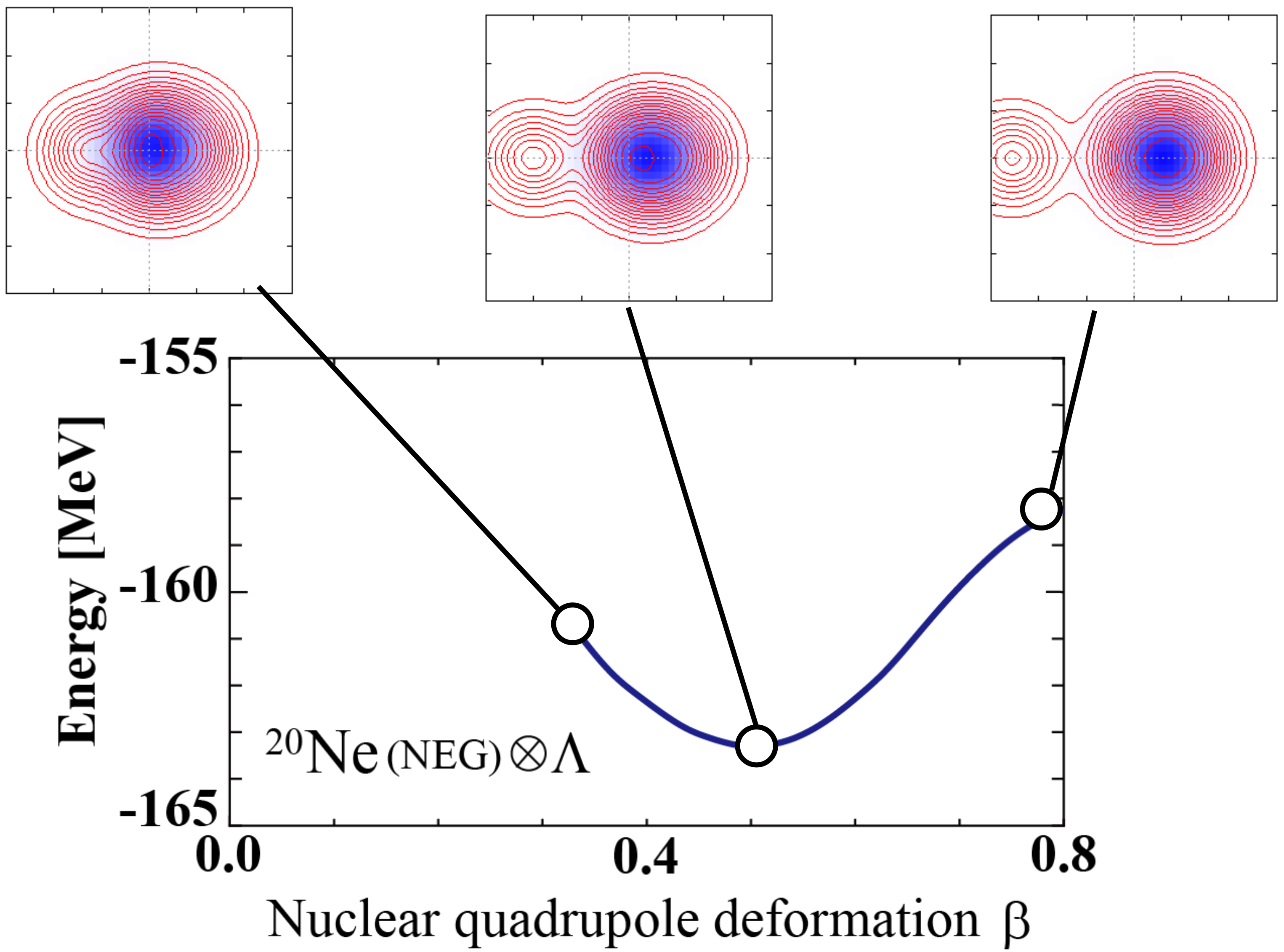
M. Isaka, et al., PRC**83**, 054304(2011)

Example:

AMD calc



$\alpha + {}^{16}O + \Lambda$ states



Λハイパー核の構造として期待できること

- glue-like role: Λ粒子により、非束縛状態が束縛する

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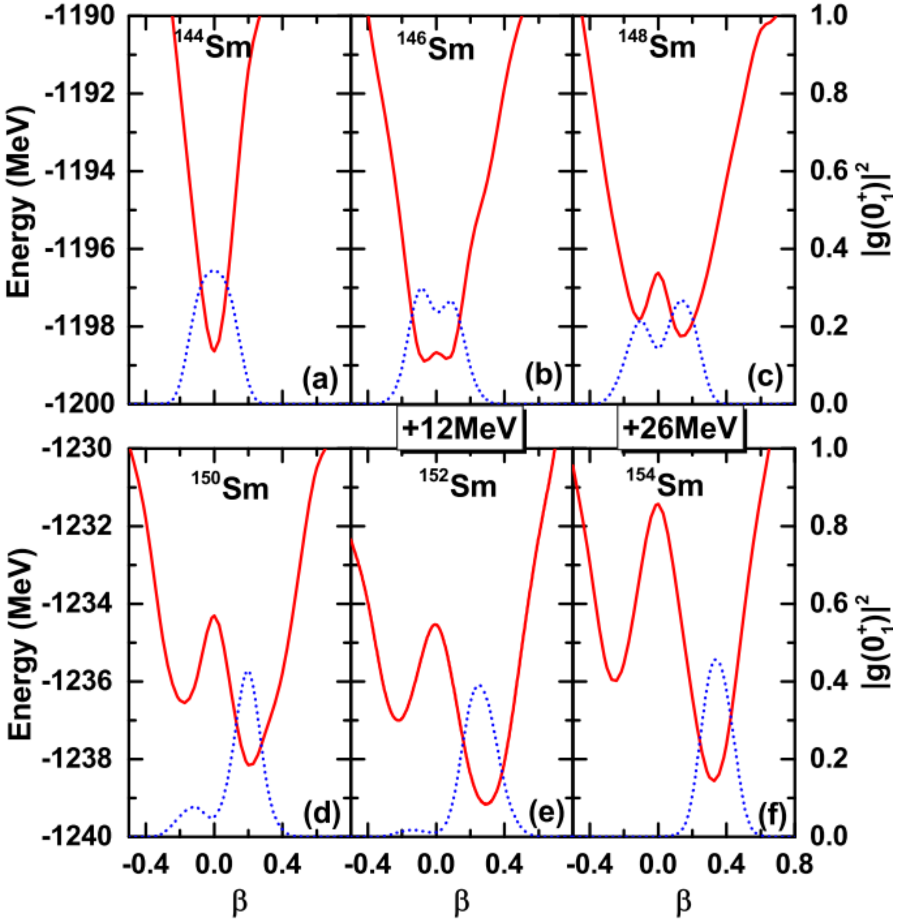
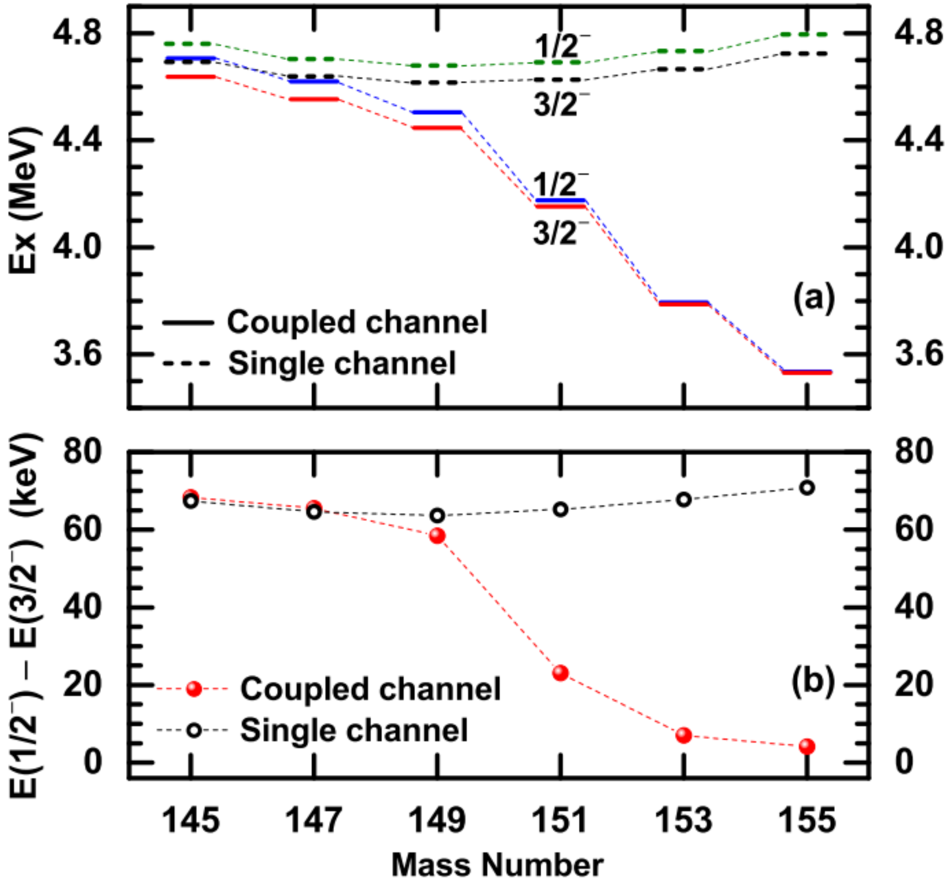
- Λ粒子が変形状態に結合することで現れる新奇な状態

Λ in *p* orbit coupled to deformed nuclei

H. Mei, K. Hagino, J. M. Yao, T. Motoba, Phys. Rev. C**96**, 014308(2017)

- Nuclear deformation affects excitation energy and energy spacing of p states
- Sm isotopes: vibrational (spherical) to rotational (deformation) character



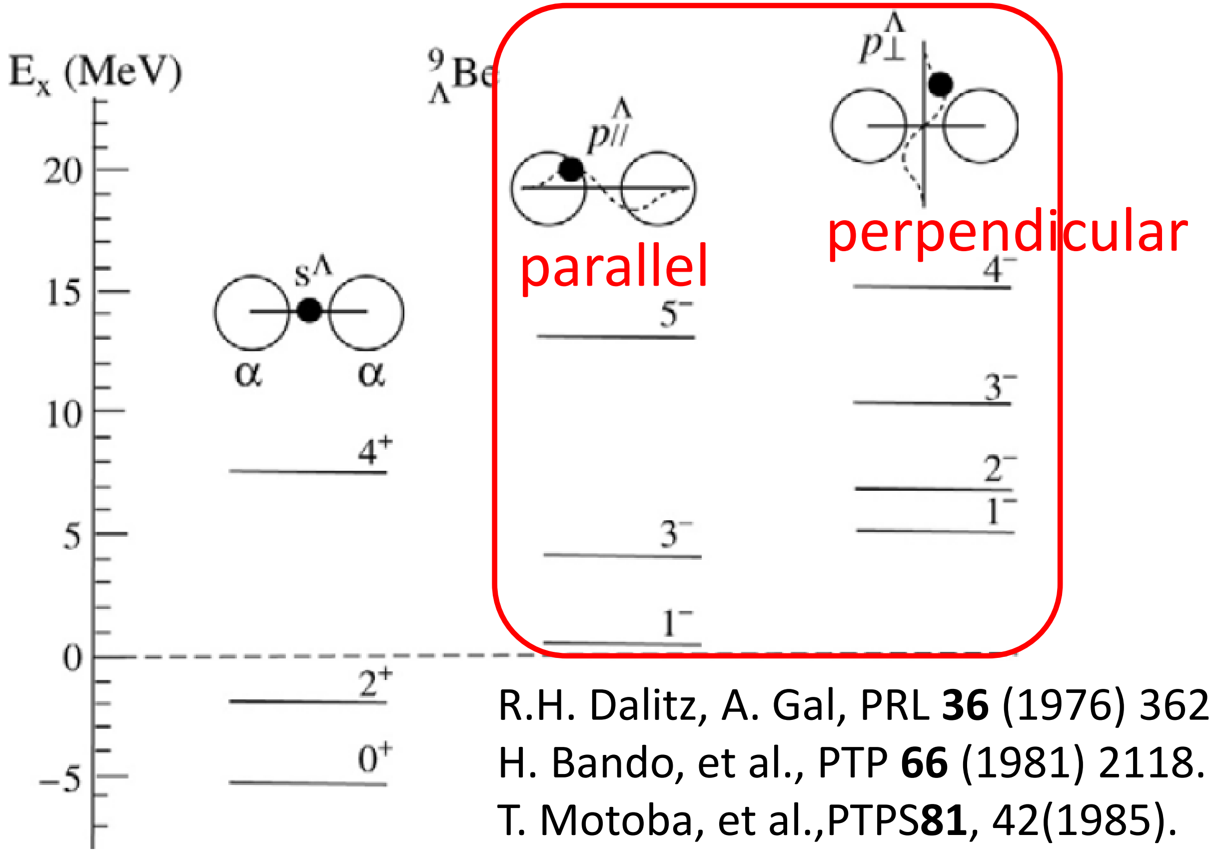


Λ in *p* orbit coupled to deformed nuclei

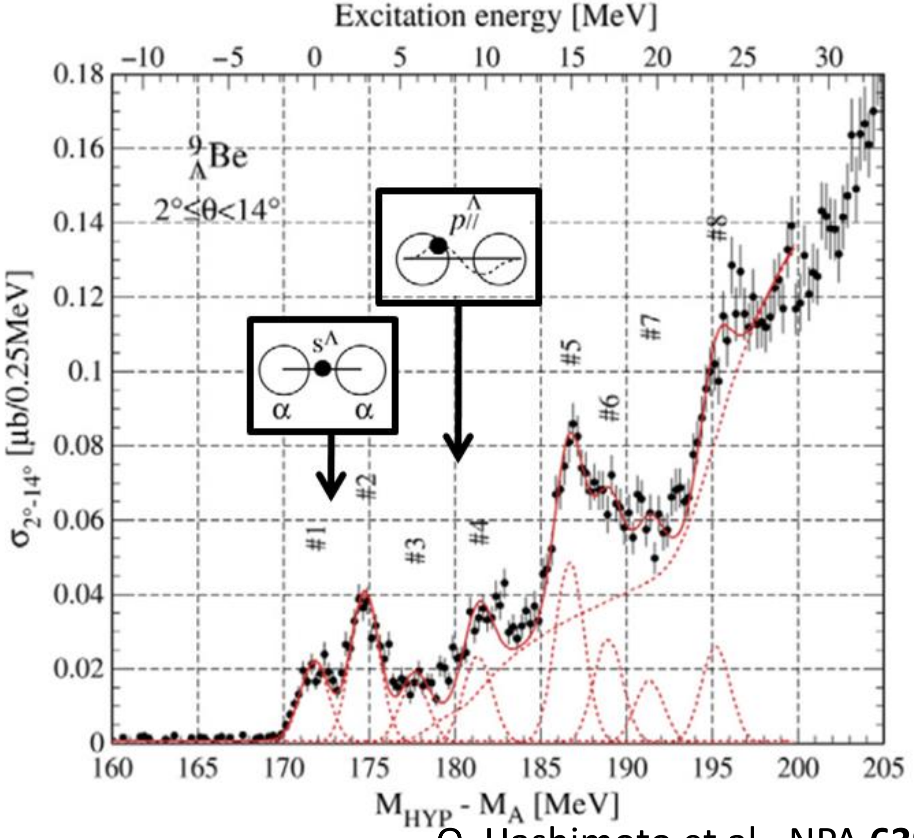
$^{9}_{\Lambda}$Be: axially symmetric 2α clustering

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).

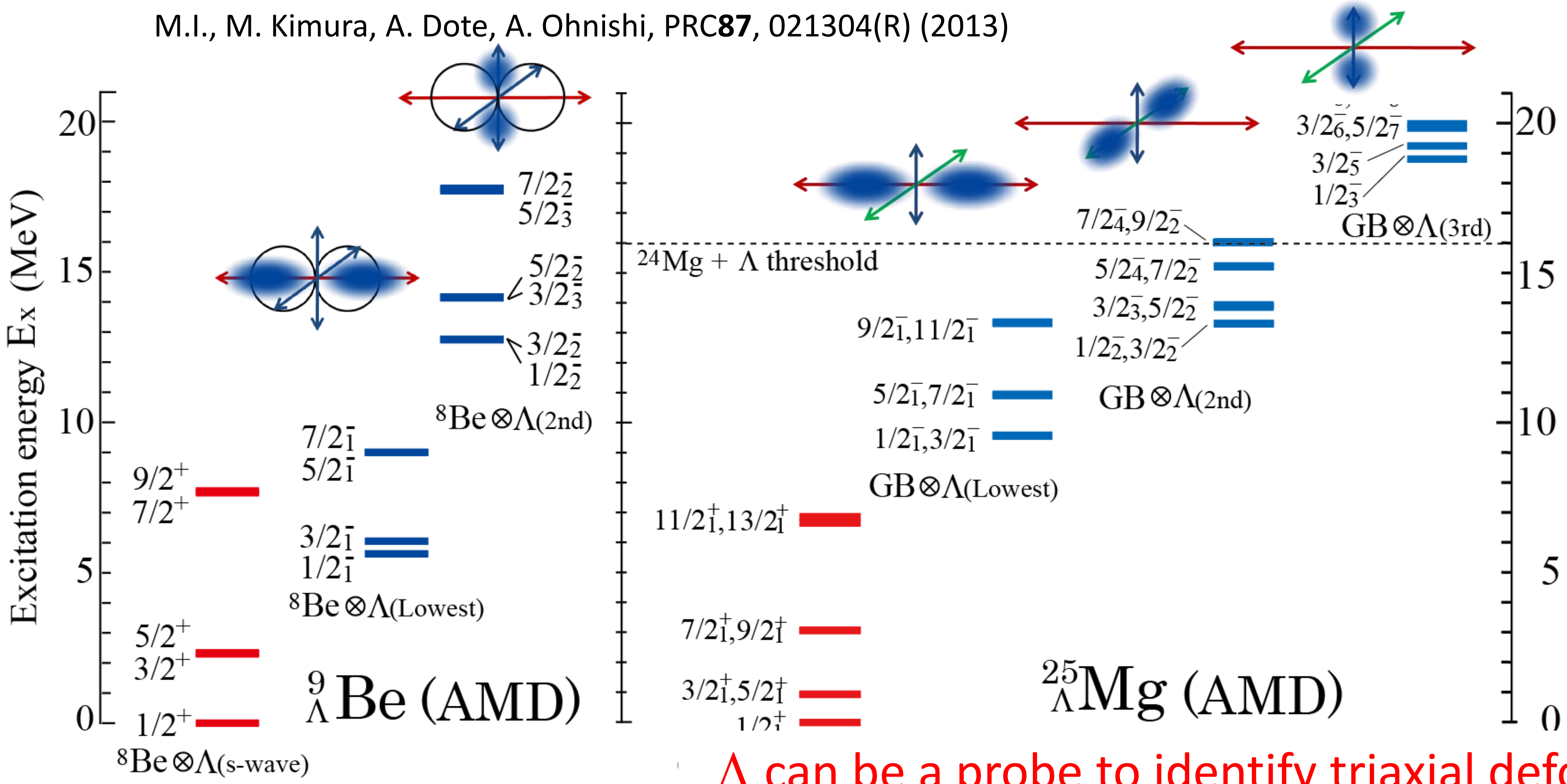


O. Hashimoto et al., NPA **639** (1998) 93c.

Λ in *p* orbit coupled to deformed nuclei

Splitting of p orbit with triaxial deformation → 3 different p states

M.I., M. Kimura, A. Dote, A. Ohnishi, PRC**87**, 021304(R) (2013)



Λ can be a probe to identify triaxial deformation

Λ in *p* orbit coupled to deformed nuclei

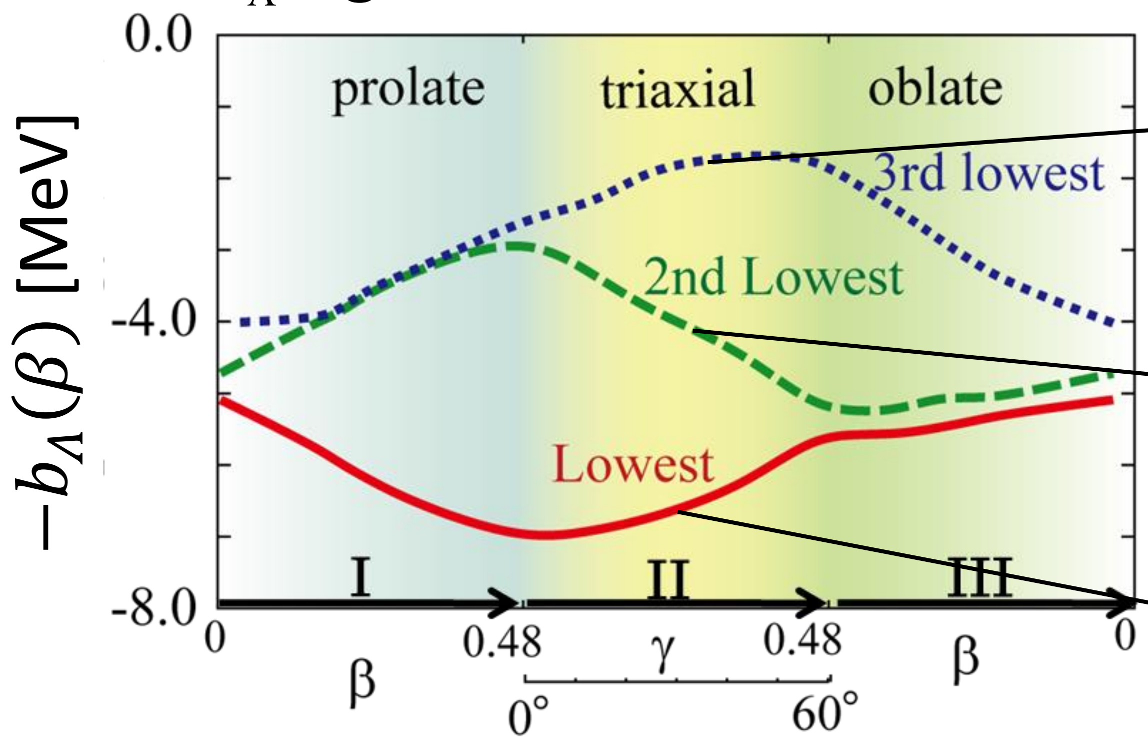
M.I., et al.,
PRC**87**, 021304(R) (2013)

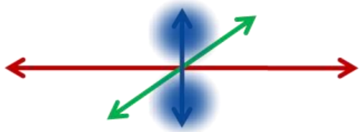
Splitting of p orbit with triaxial deformation → 3 different p states

- 3 *p*-states with different spatial distributions of Λ
- Λ binding energy $b_\Lambda(\beta)$ is different each other due to triaxial deformation

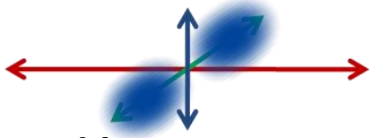
$^{25}_{\Lambda}$Mg

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

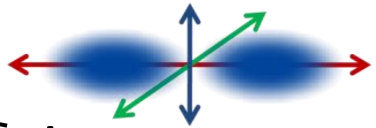




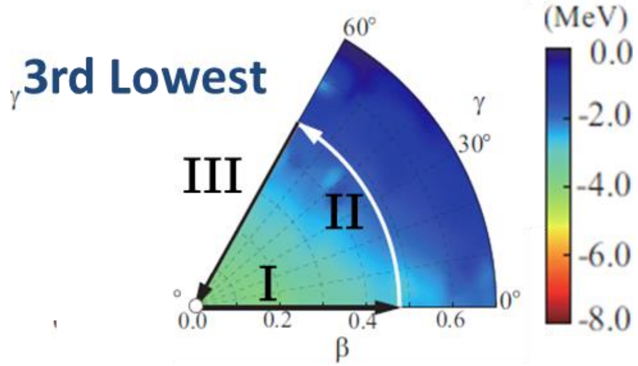
3rd lowest p state
(Parallel to short axis)

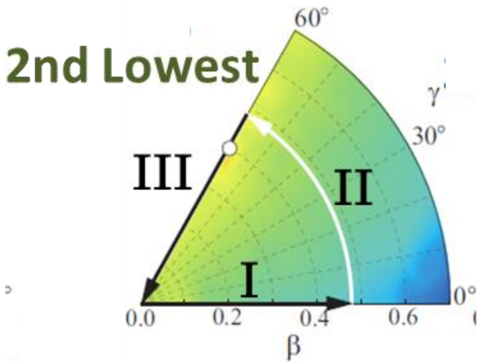


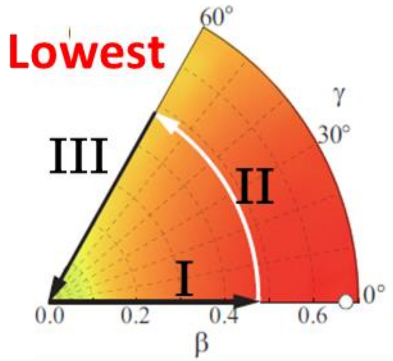
2nd lowest p state
(Parallel to middle axis)



Lowest p state
(Parallel to long axis)

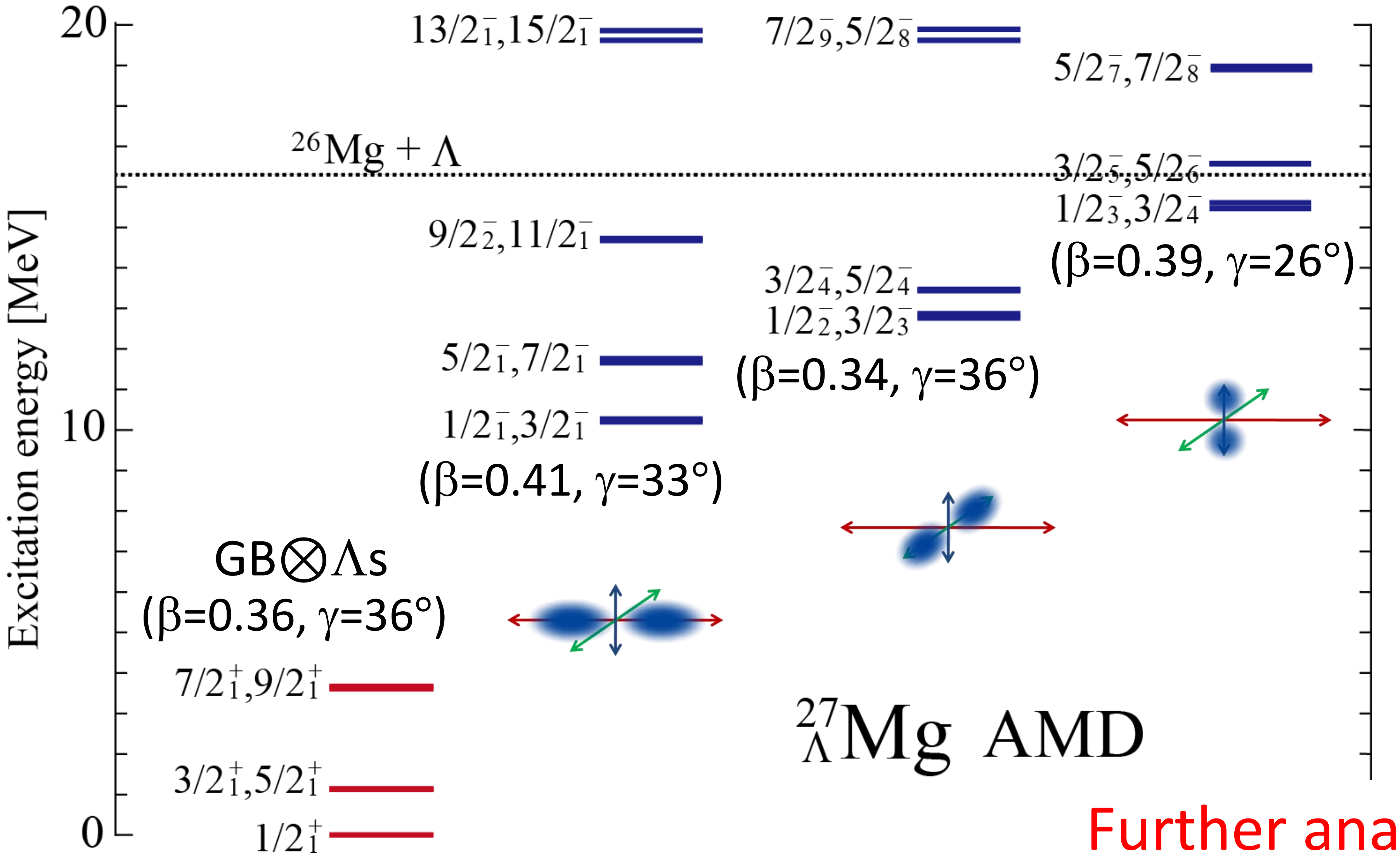






Λ in *p* orbit coupled to deformed nuclei

- **Possibility of $^{27}_{\Lambda}$Mg in future JLab experiments**



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

Further analysis is ongoing

生成断面積：非束縛状態の構造を引き出したい

Production cross section of hypernuclei with AMD wave functions to see effects of various structures

- **In future: (γ, K⁺) reaction**

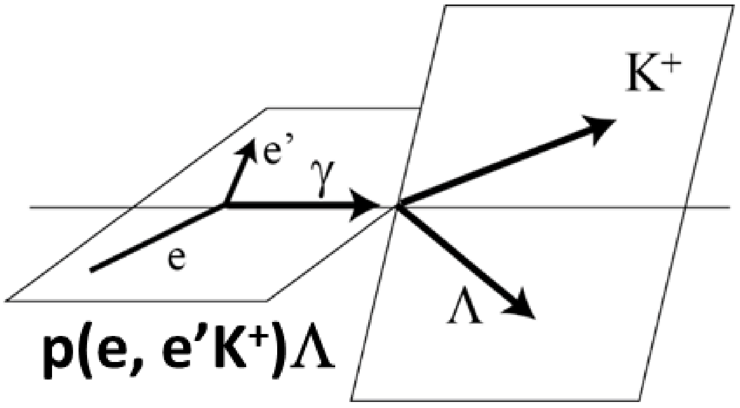
T. Motoba *et al.*, PTP**185**, 224(2010)

$$\frac{d\sigma}{d\Omega}(\theta_K^{\rm Lab}) = \frac{s p_K^2 E_K E_H}{p_K(E_H+E_K) - E_\gamma E_K \cos\theta_K^{\rm Lab}} \sum_{M_f} R(fi;M_f),$$

$$R(fi;M_f) = \frac{1}{2J_i+1}\sum_{M_i} \Psi_{\rm GCM}^{J_f\pi M_f} |\langle \Psi_{\rm GCM}^{J_f\pi M_f}|O|\Psi_{\rm GCM}^{J_i\pi M_i}\rangle|^2$$

AMD + GCM wave functions

Various structure



$$O = \int d^3r \chi_K^{(-)*}(\mathbf{p},\xi\mathbf{r})\chi_K^{(+)}(\mathbf{k},\mathbf{r}) \sum_{j=1}^{A} V_-^{(j)} \delta(\mathbf{r}-\eta\mathbf{r}_j) \langle \mathbf{k}-\mathbf{p},\mathbf{p}|t|\mathbf{k},0\rangle$$

Plane wave

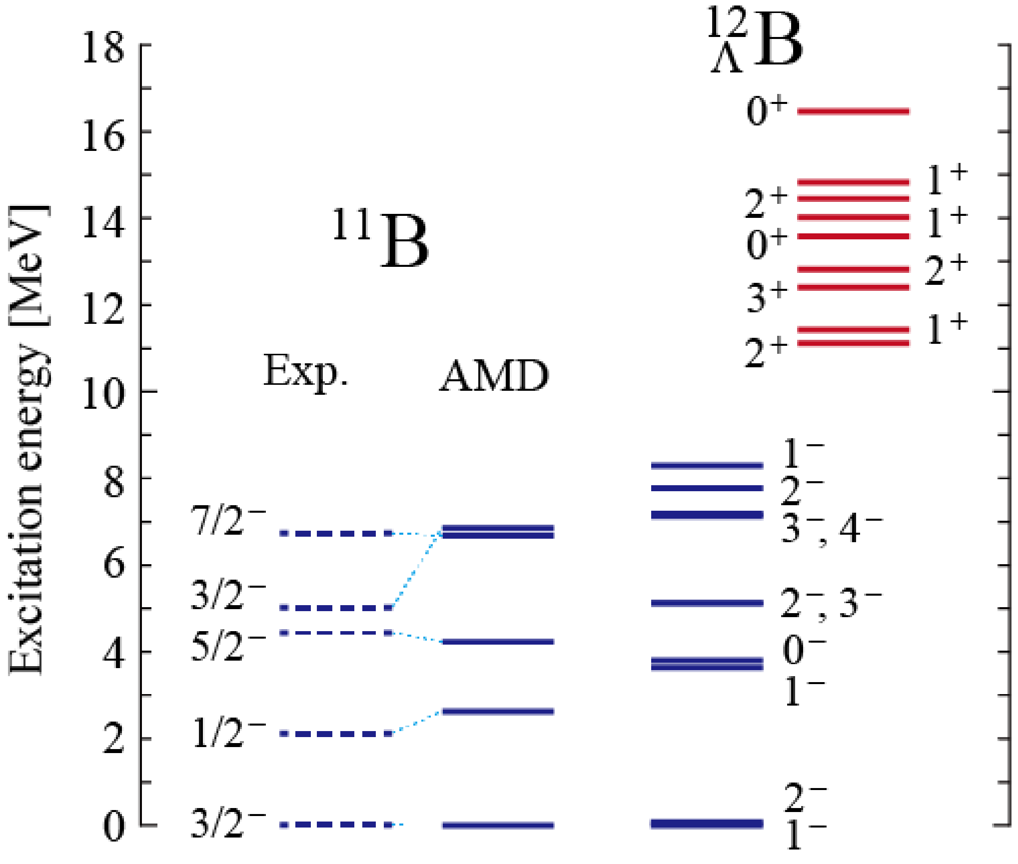
→ Distorted wave

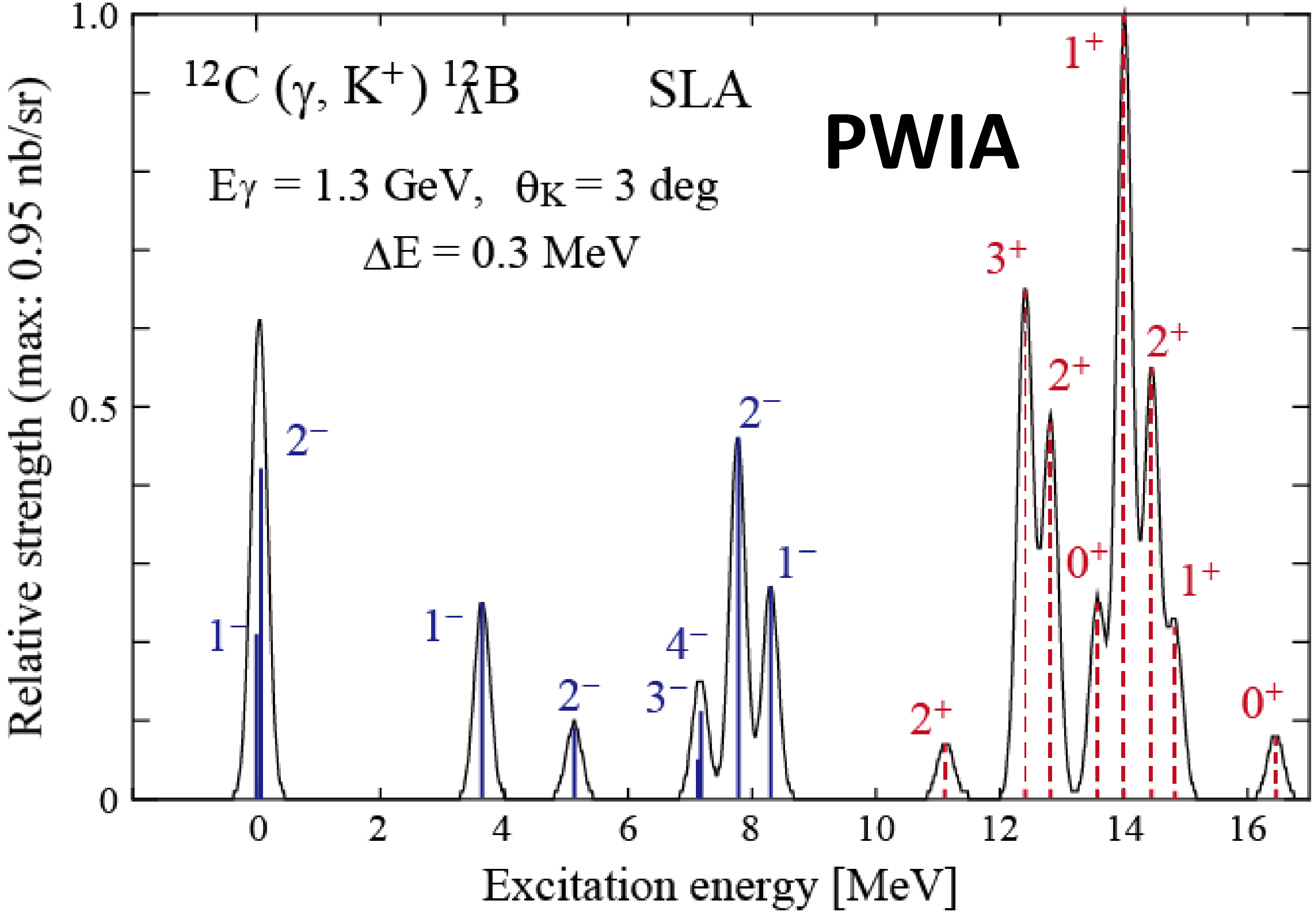
Elementary amplitude

- **Current status: PWIA based on effective nucleon number approach**

生成断面積:非束縛状態の構造を引き出したい

◆Example: $^{12}C(g, K^+)^{12}{}_{\Lambda}B$

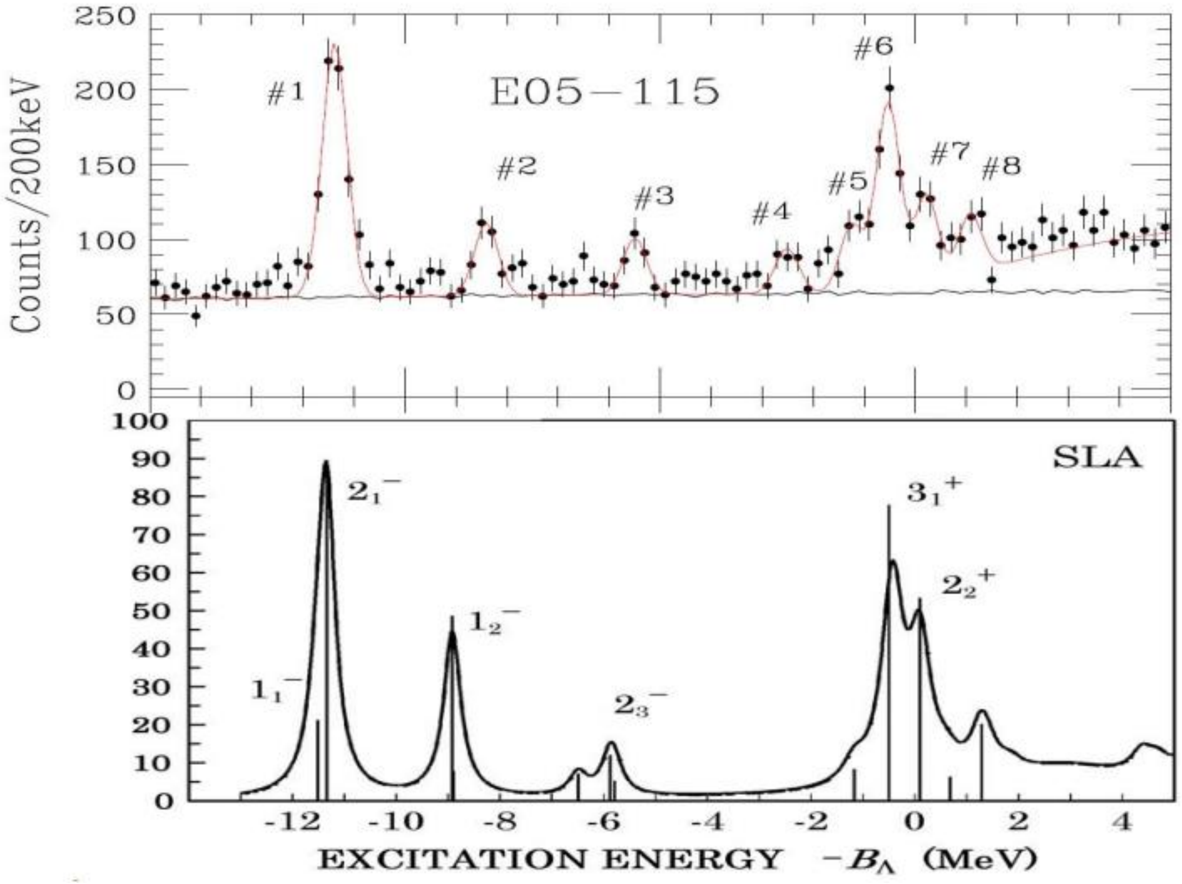




生成断面積：非束縛状態の構造を引き出したい

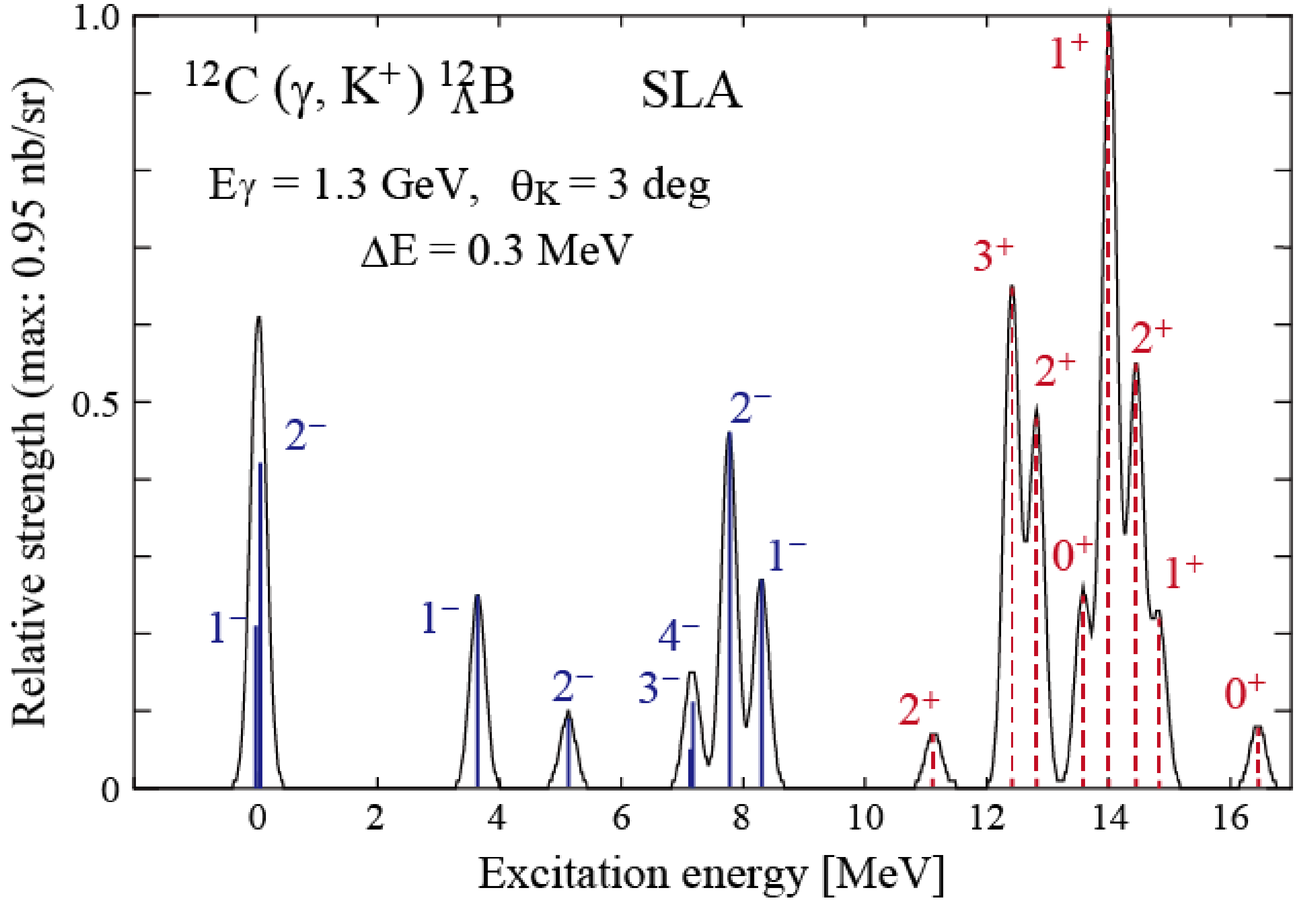
◆Example: $^{12}C(g, K^{+})^{12}{}_{\Lambda}B$

L. Tang, et al.,PRC**90**, 034320(2014)



T. Motoba, JPS.Conf.Proc.17,011003(2017)

HyperAMD(present), PWIA



Summary

◆Λ粒子が原子核に加わると、何が起こるか？

- **glue-like role: Λ粒子により、非束縛状態が束縛する**

- **構造の動的変化：変形の変化、核半径の収縮**
  - “binding energy of Λ” vs. “energy curve of the core nuclei”
  - Large shrinkage in cluster states

- **変形・構造の違いに対するエネルギー（B_Λ）の違い**
  - Shift-up/down in excitation spectra, if different structure coexist

    例）${}^{A}_{\Lambda}$Be：2αクラスター構造の違い、${}^{21}_{\Lambda}$Ne：平均場とクラスター

- **Λ粒子が変形状態に結合することで現れる新奇な状態**
  - Deformation can affect excitation spectra/rotational bands of *p*-states

    例）${}^{27}_{\Lambda}$Mg：Λをプローブとして核の三軸非対称変形をidentifyできるか