Nuclear structure probed by hyperons with Antisymmetrized Molecular Dynamics

Masahiro Isaka (Hosei University)

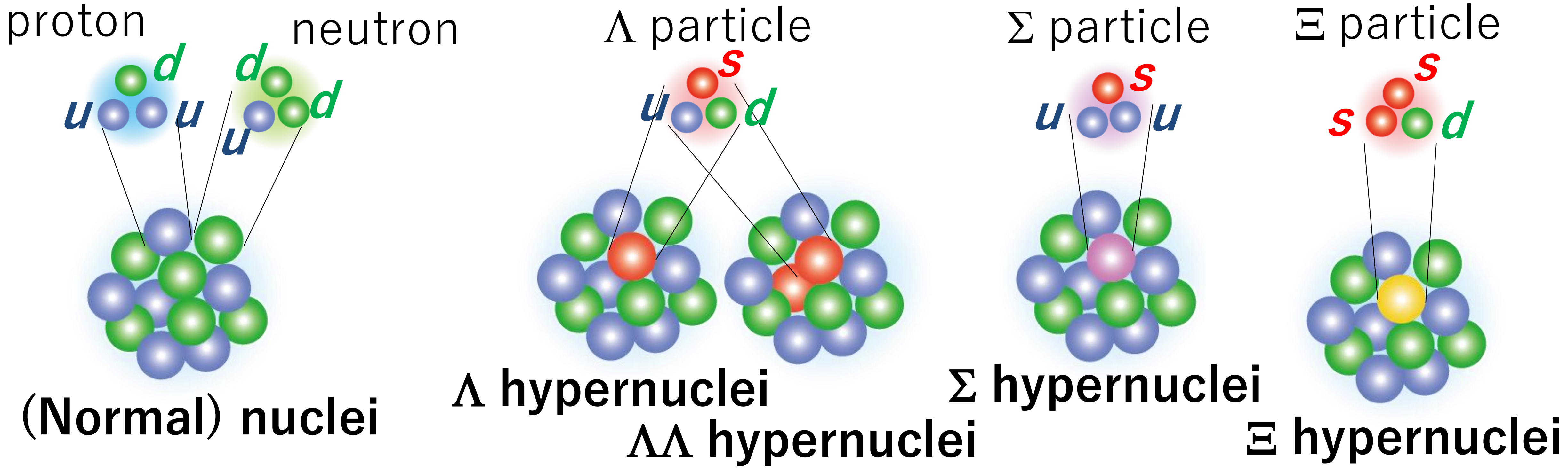
Hypernucleus

◆Normal nuclei

- **Nucleons**
  - proton & neutron

◆Hypernuclei

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



These hypernuclei can be produced by experiments

Grand challenges of hypernuclear physics

Interaction: "baryon-baryon interaction"

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

Major issues in hypernuclear physics

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

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

  e.g. **structure change by hyperon(s)**
  - No Pauli exclusion between N and Y
  - YN interaction is different from NN

Hyperon as an impurity in nuclei

"impurity effects": nuclear structure change by hyperon(s)

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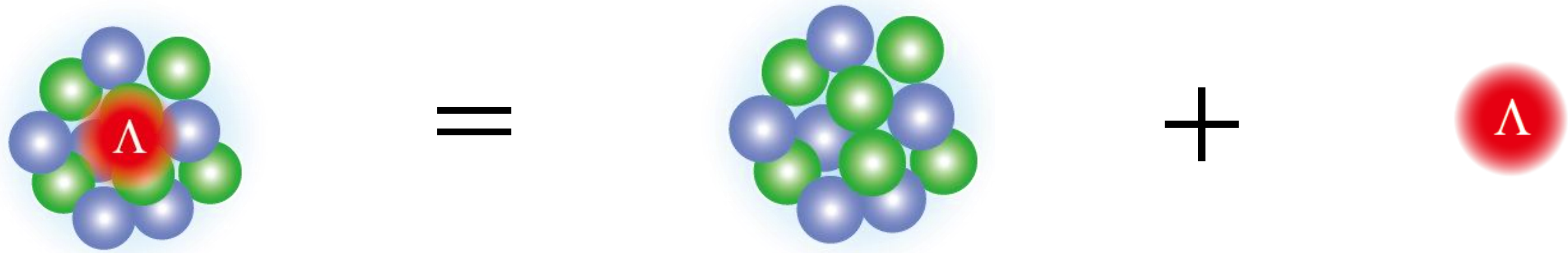

Λ hypernucleus　　Normal nucleus　　An impurity

"impurity effects": nuclear structure change by hyperon(s)

Grand challenges of hypernuclear physics

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"impurity effects": nuclear structure change by hyperon(s)

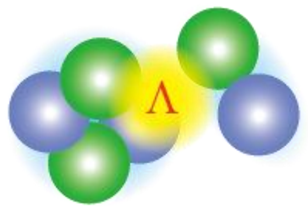
Structure of Λ hypernuclei

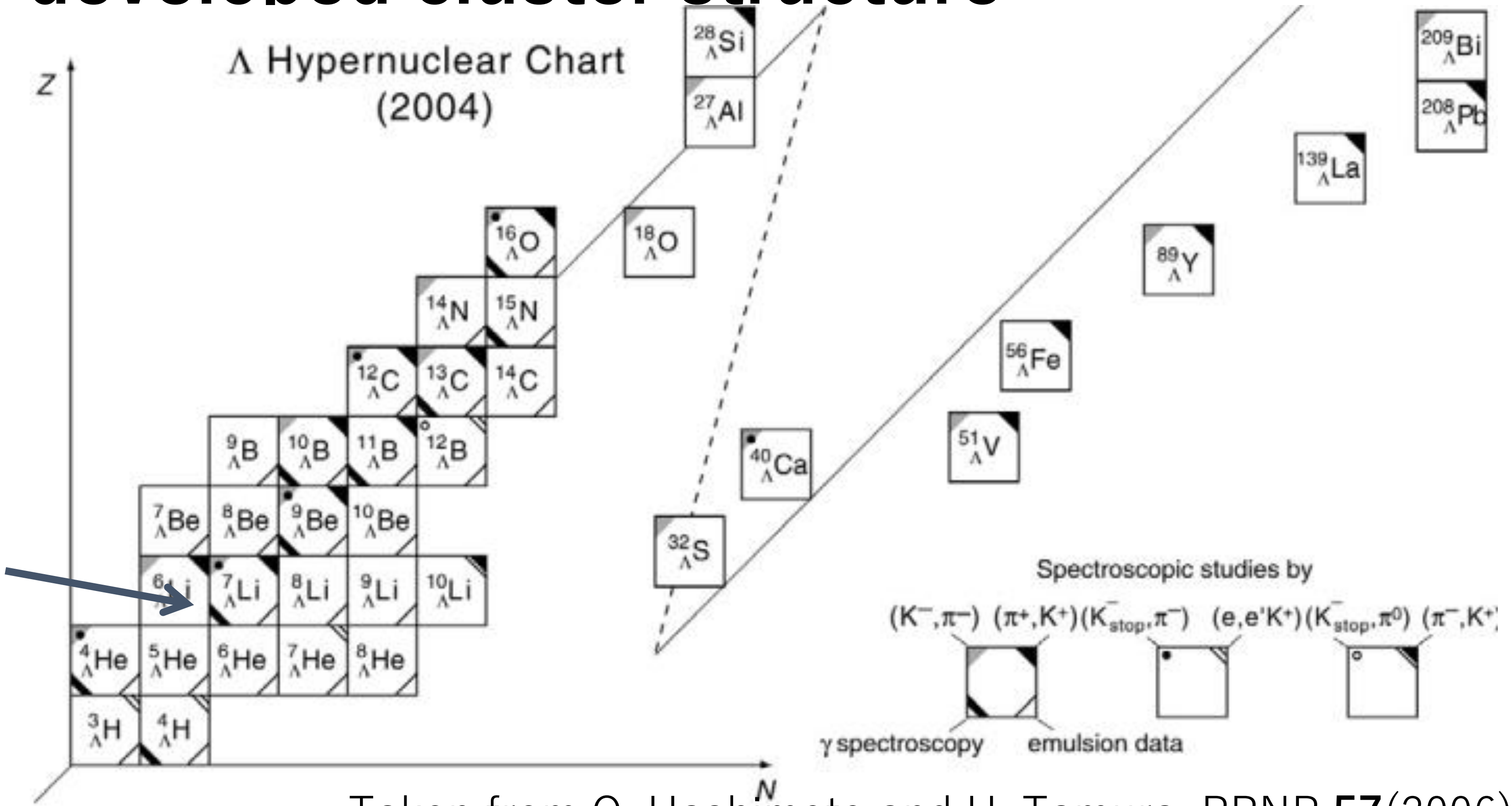
◆Λ hypernuclei observed so far

- **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.

Structure of Λ hypernuclei

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- ●**Concentrated in light Λ hypernuclei**
- ●**Most have well-develope**

Light Λ hypernuclei

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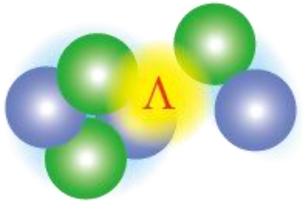
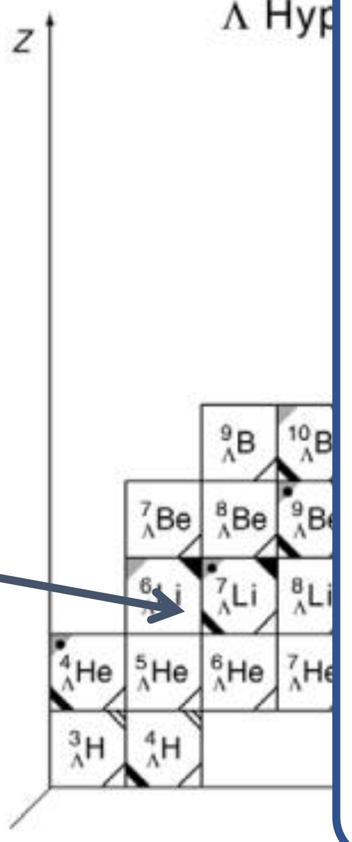




Changes of cluster structure

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 between α + d
- Confirmed through B(E2) reduction

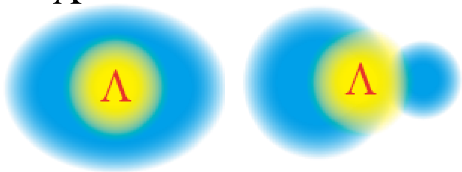
Toward heavier and exotic Λ hypernuclei

◆Experiments at J-PARC, JLab, *etc.*

- ●Heavier(*sd*-shell) & n-rich hypernuclei can be produced
- ●Various structures will appear

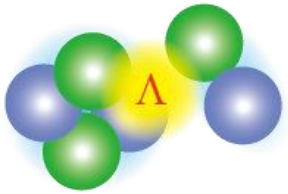
Coexistence of structures

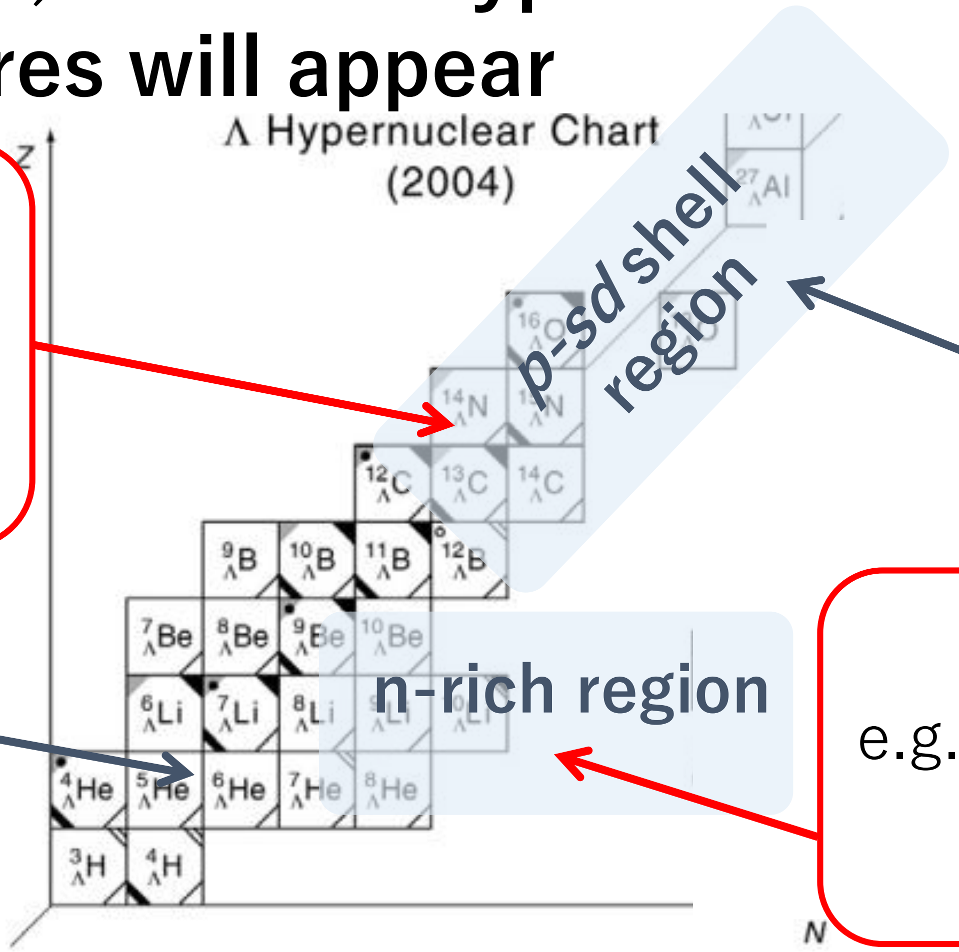
e.g. $^{21}_{\Lambda}$Ne



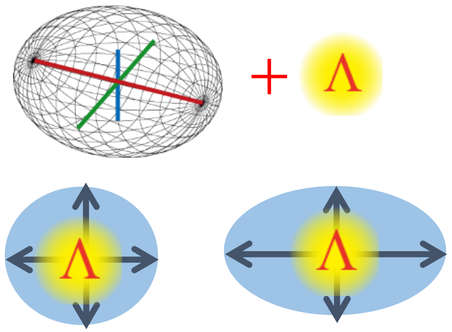
Light Λ hypernuclei

Developed cluster



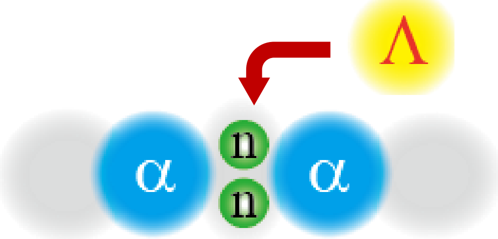


Various deformations



Exotic cluster

e.g. $^{12}_{\Lambda}$Be



How does a Λ modify structures of *p-sd* shell/n-rich nuclei ?

Structure study based on recent achievements

◆Knowledge of ΛN interaction: from Λ hypernuclei

- **Few-body calculation techniques**
- **ΛN G-matrix effective interactions**
- **Increase of experimental data**

Hiyama, NPA **805** (2008)
Yamamoto, *et al.*, PTP Suppl. **117** (1994)
Hashimoto and Tamura, PPNP **57** (2006)

◆Developments of nuclear structure models

- **Example: Antisymmetrized Molecular Dynamics (AMD)**
  - In structure studies on stable and n-rich nuclei
  - Describe dynamical changes of various structure
  - No assumption on α clustering and specific deformation

Kanada-En'yo *et al.*, PTP **93** (1995)

Recent developments enable us to study structure of Λ hypernuclei

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 (NF, NSC97f, ESC08c)

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

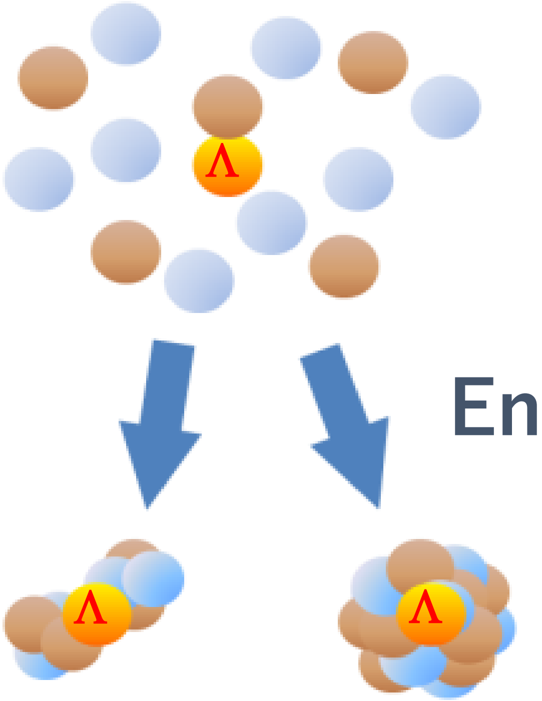
Theoretical Framework: HyperAMD

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

◆Procedure of the numerical calculation

Variation

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



Initial w.f.: randomly generated

Energy variation

Various deformations
and/or cluster structure

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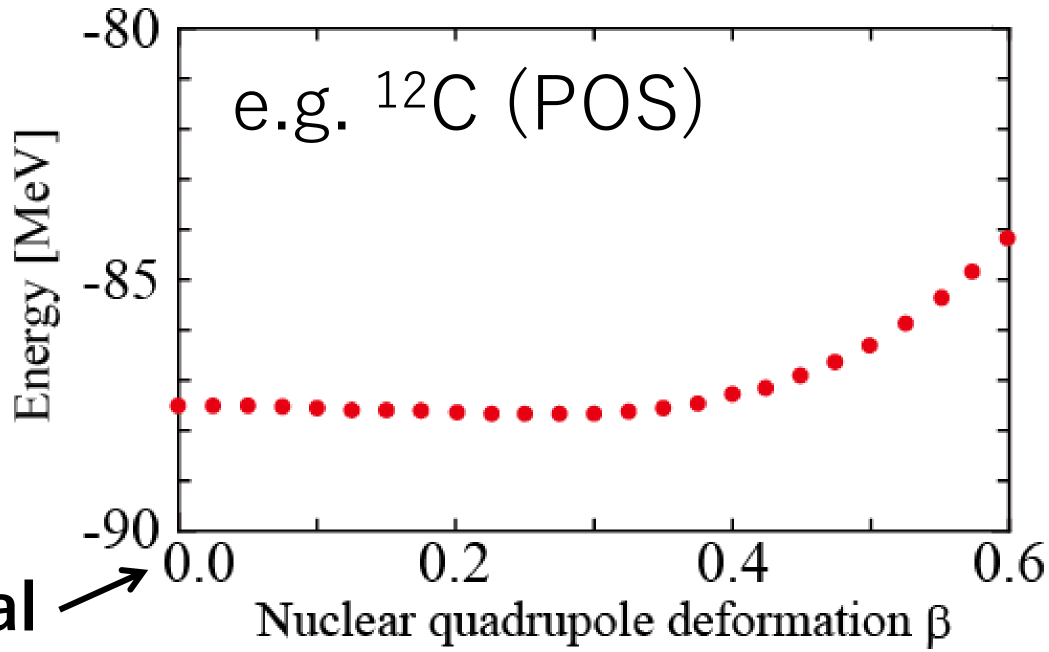
Actual calculation: Constraint on nuclear quadrupole deformation

- Deformation param.: β (& γ)
- Parity-projection
- Variation at each β

Energy surface as a function of β

β = 0.0
Spherical



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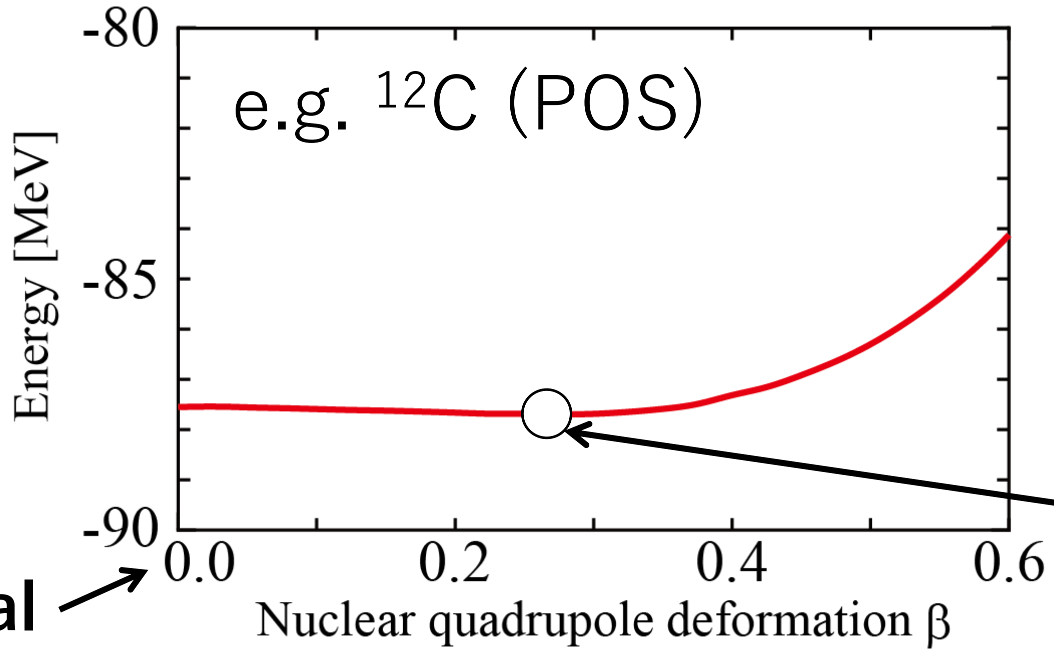
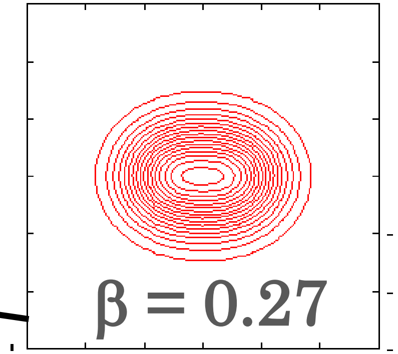


Nuclear density at the minimum



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

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

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

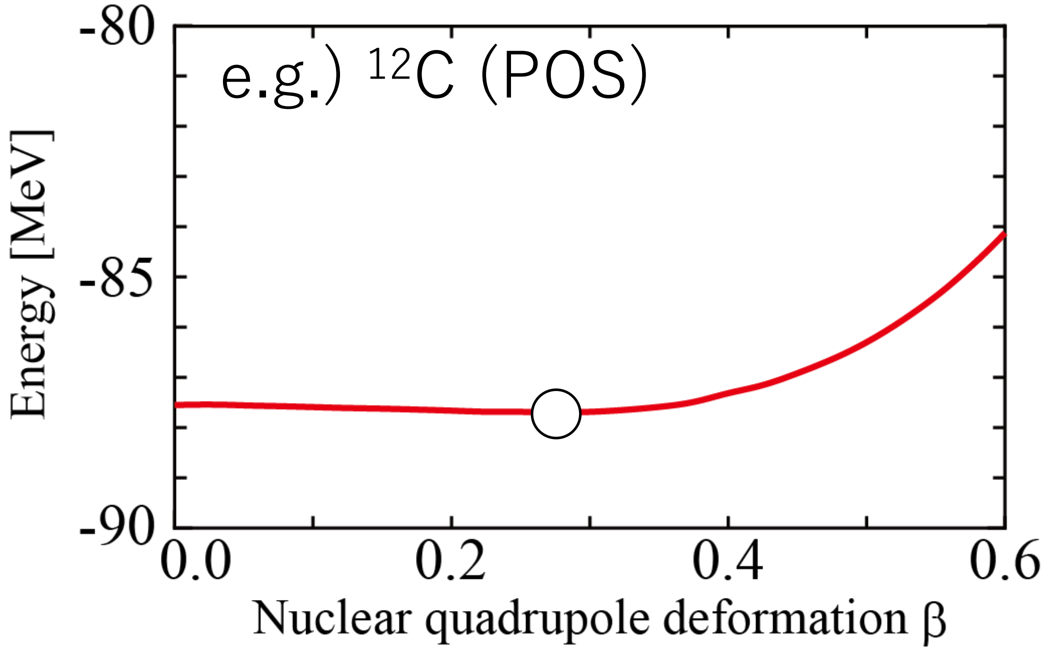
$$\left|\Psi^{J\pm M}\right\rangle = \sum_{sK} g_{sK} \left|\Phi_K^s; J^{\pm}M\right\rangle$$

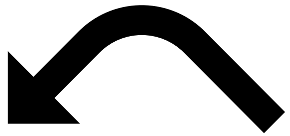
w.f. on energy curve are used as basis of the GCM calculation

1. Deformation changes by Λ particle

How does Λ change the energy surface?

Examples: $^{13}_{\Lambda}C$ (, $^{9}_{\Lambda}Be$, $^{20}_{\Lambda}Ne$, $^{21}_{\Lambda}Ne$)



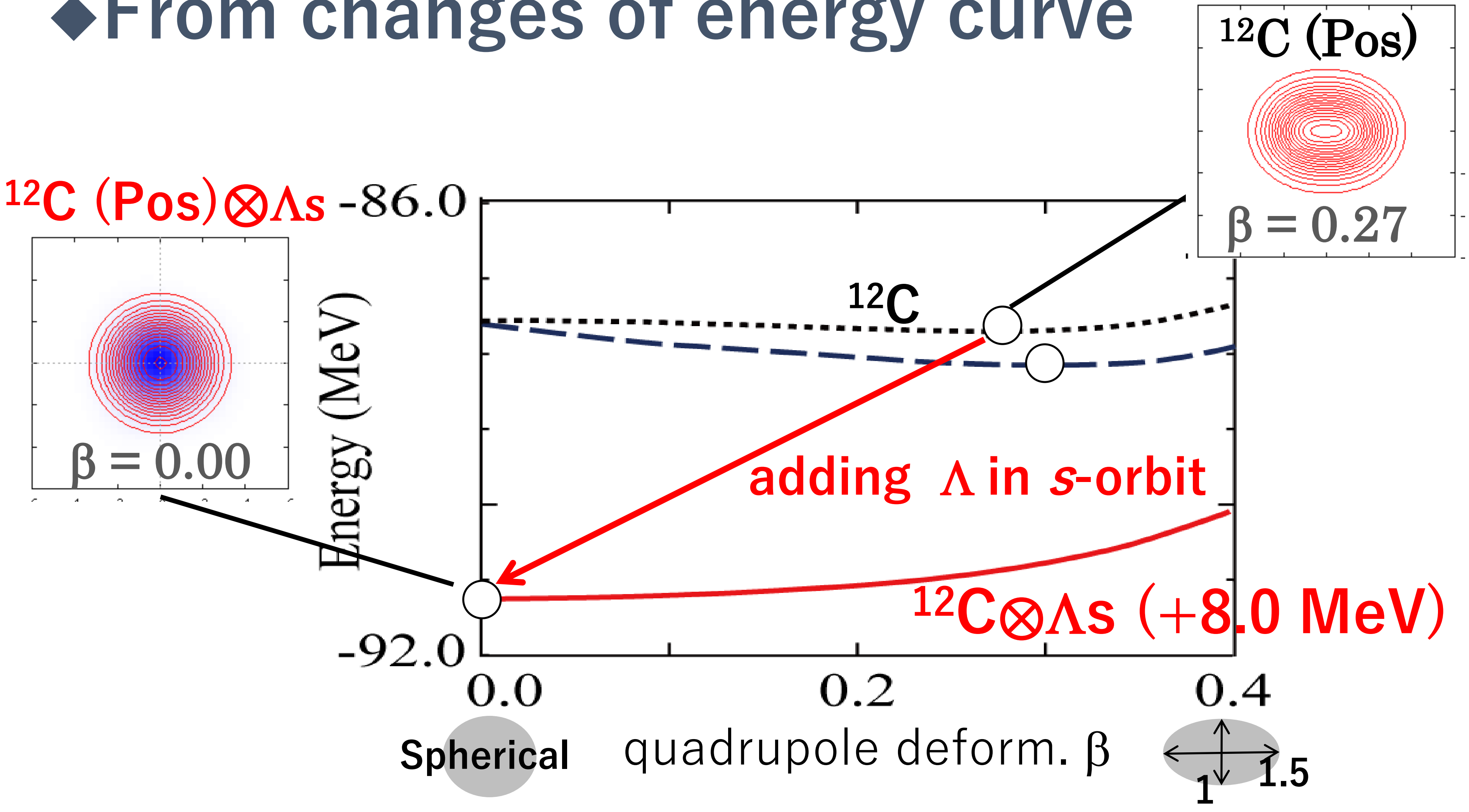


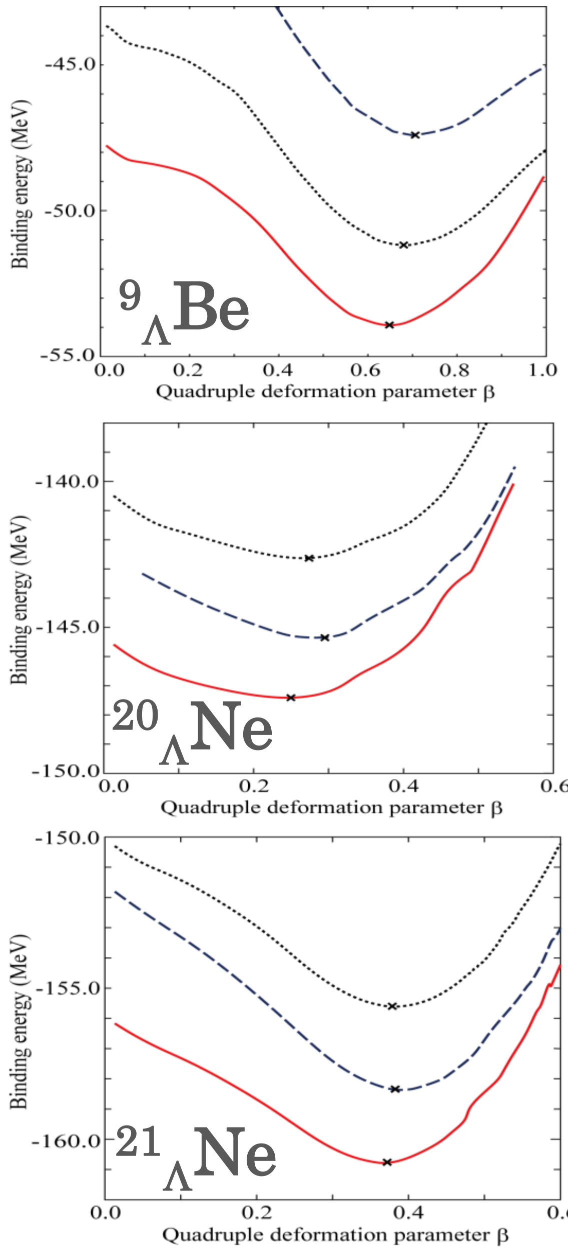
General trend of impurity effects by a Λ particle

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

Deformation change by Λ in *s*-orbit

◆**From changes of energy curve**



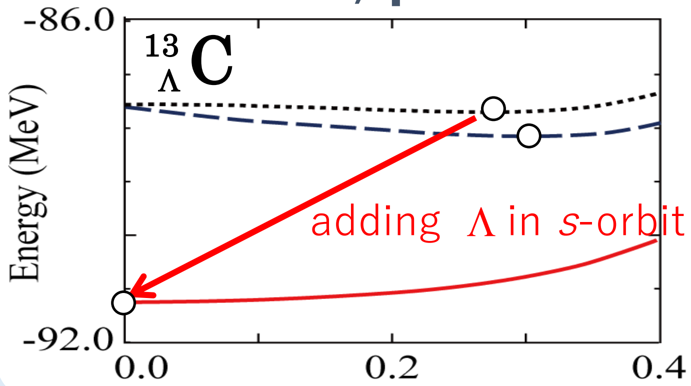


Λ in *s*-orbit reduces the nuclear deformation

Deformation change by Λ in *s*-orbit

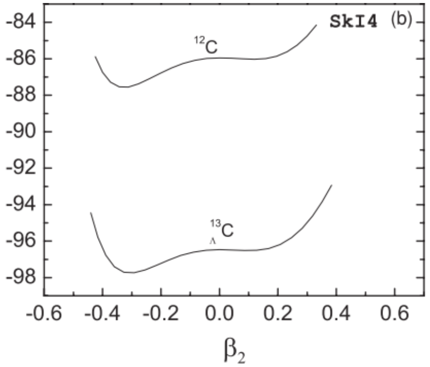
Many authors predicted the deformation changes by Λ in *s*-orbit

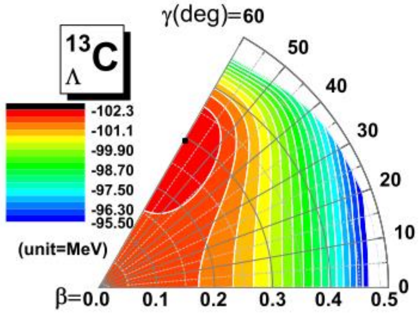
AMD, present



Skyrme-Hartree-Fock (SHF)

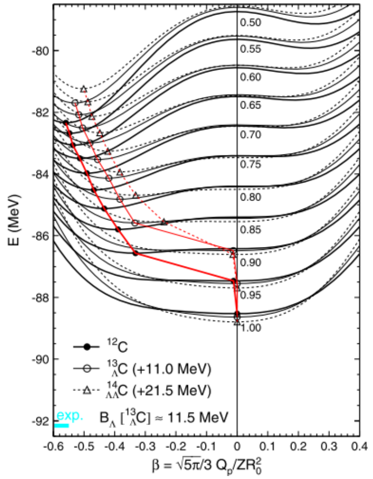
X.R. Zhou, et al., PRC**76**, 034312('07)
J.W. Cui, X.R. Zhou, H.J. Schulze, PRC**91**,054306('15)





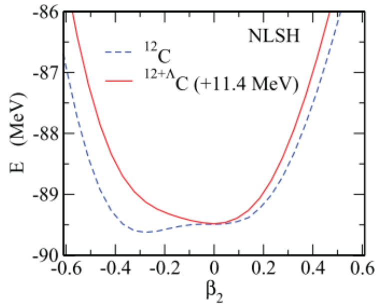
RMF & SHF

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

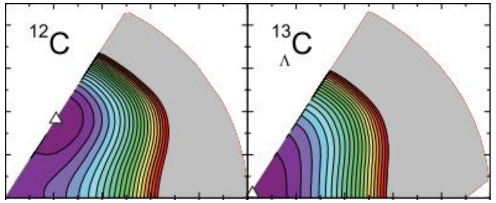


Relativistic mean-field (RMF)

Win and Hagino, PRC**78**, 054311('08)



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



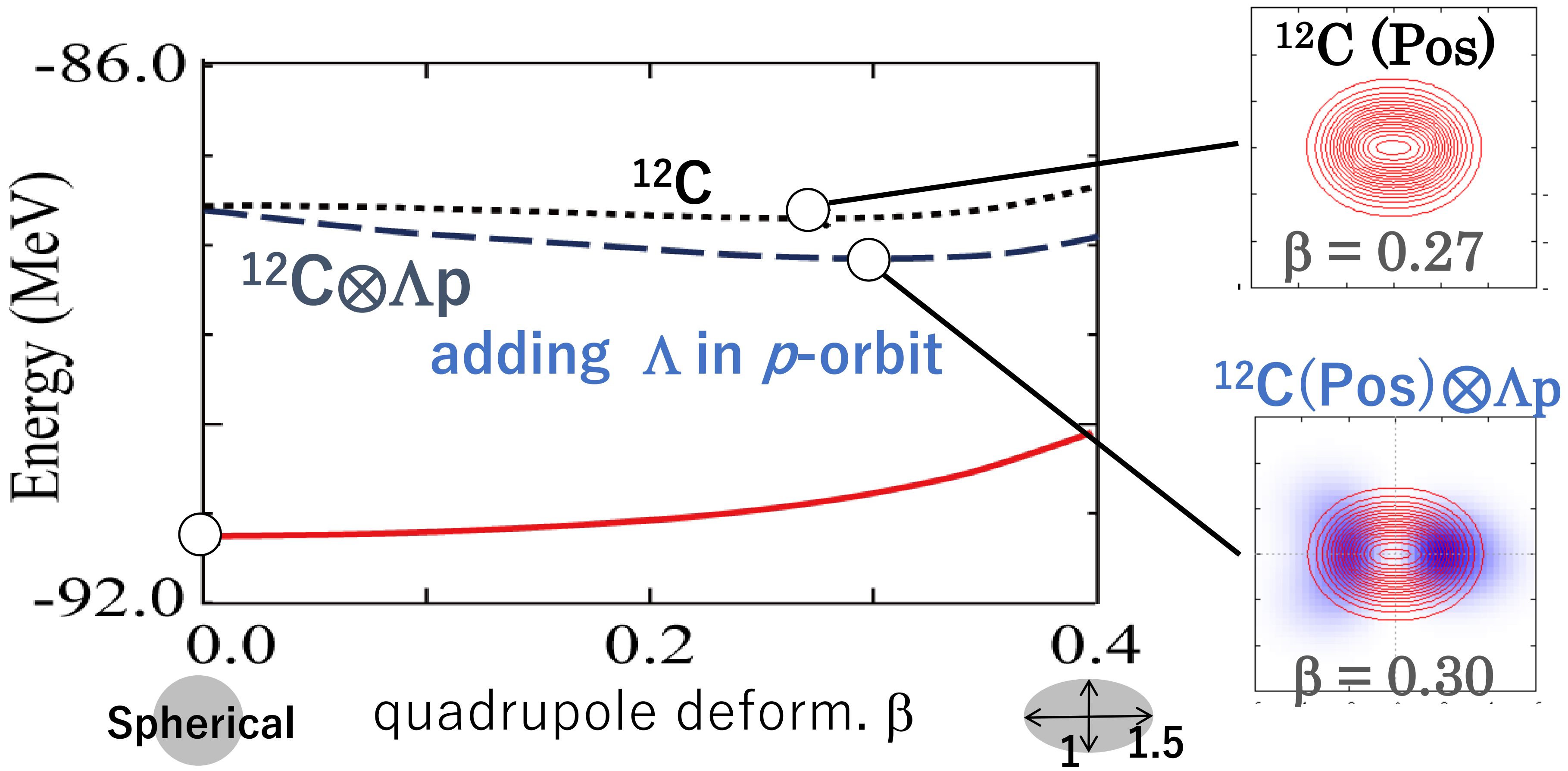
Deformations/level structure with beyond-mean-field

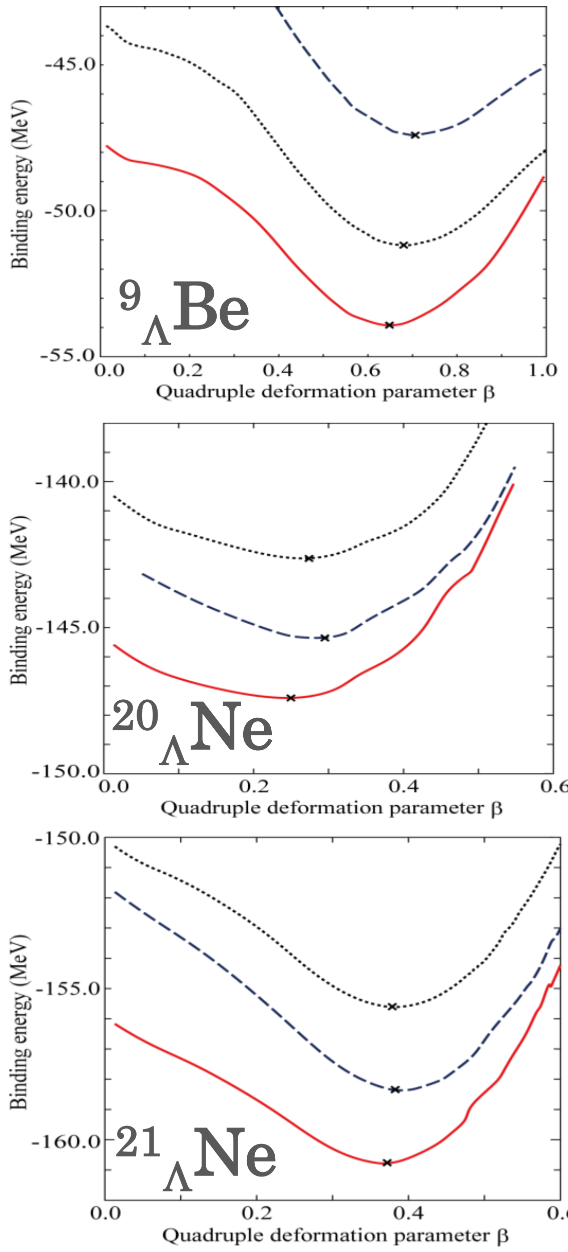
J.W. Cui, X.R. Zhou, H.J. Schulze, PRC**91**,054306('15)
H. Mei, K. Hagino, J.M. Yao, T. Motoba, PRC**91**, 064305('15)

etc.

Deformation change by Λ in *s*-orbit

◆From changes of energy curve





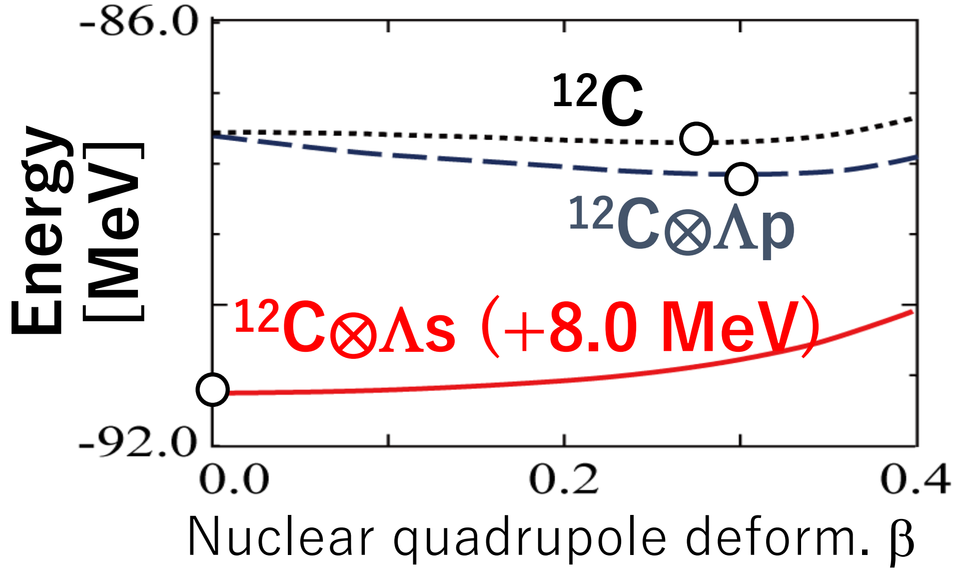
Λ in *p*-orbit enhances the nuclear deformation

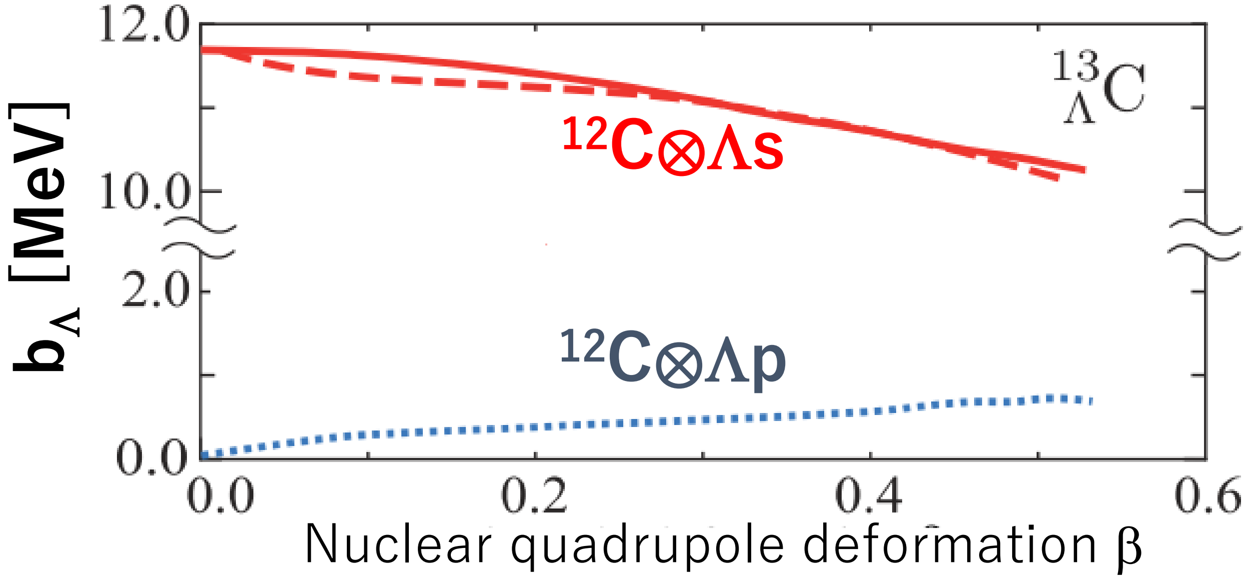
⟶ Opposite trend to Λ in *s*-orbit

Reason for deformation changes

◆Behavior of Λ binding energy

Λ binding energy as difference of the curves: $b_\Lambda = E(^{12}C) - E(^{12}C\otimes\Lambda)$





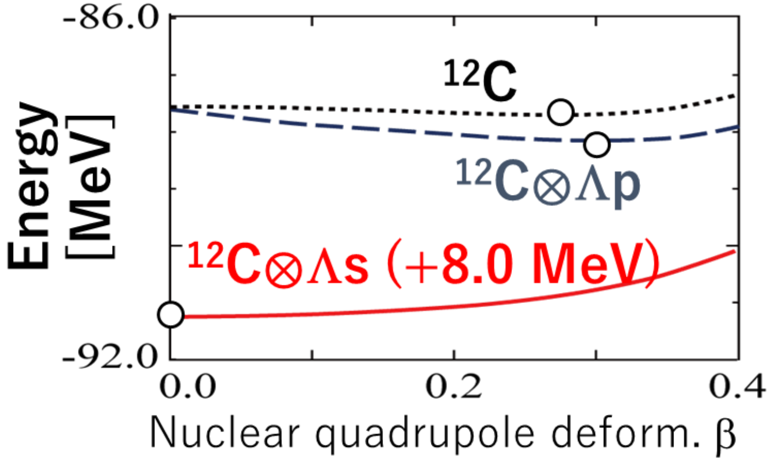
●Λ in *s*-orbit is deeply bound at smaller deformation

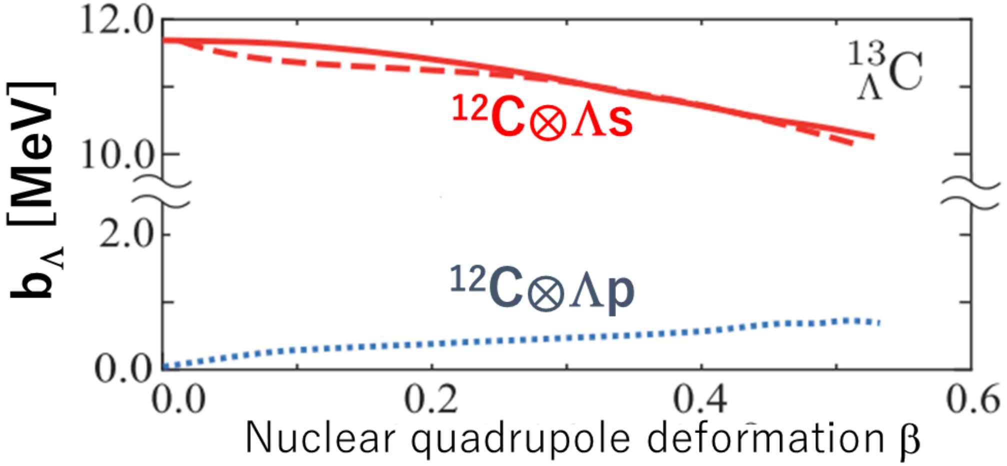
●Λ in *p*-orbit is deeply bound at larger deformation

"competition between Λ binding energy and core energy curves"

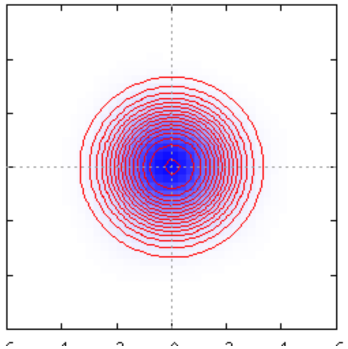
Reason for deformation changes

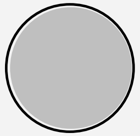
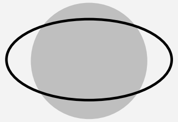
Λ in *s*-(*p*-)orbit is deeply bound at smaller (larger) deformation





^{12}C (Pos)⊗Λ*s*

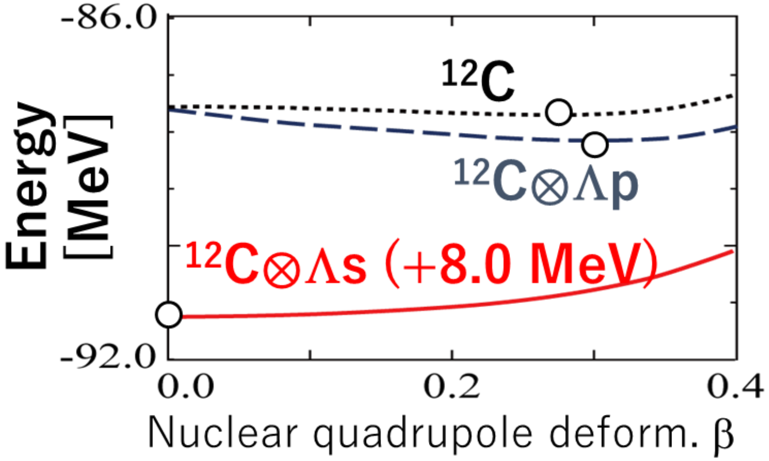


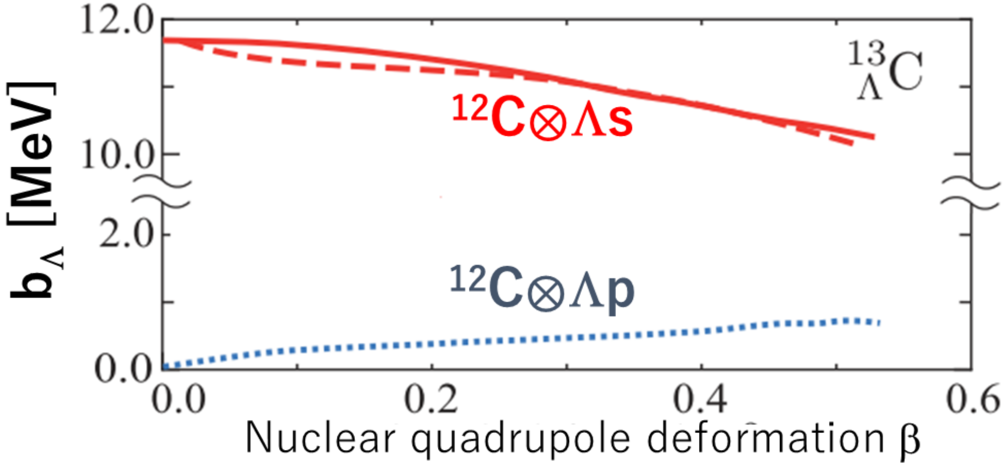
Λ in *s*-orbit	 **spherical**	 **deformed**
Overlap of Λ & N	**Larger**	**Smaller**
ΛN attraction	**Strong**	**Weak**

Overlap of Λ and nucleons is essential for Λ binding energy

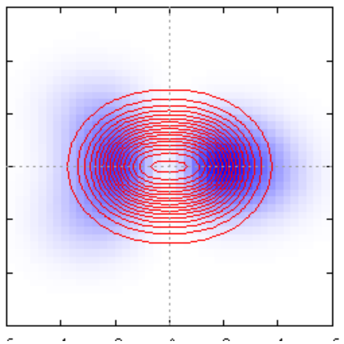
Reason for deformation changes

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





^{12}C(Pos)⊗Λp

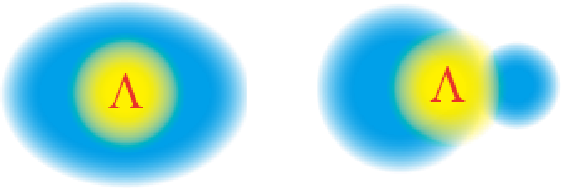


Λ in *p*-orbit	spherical	deformed
Overlap of Λ & N	Smaller	Larger
ΛN attraction	Weak	Strong

Overlap of Λ and nucleons is essential for Λ binding energy

2. Examples of impurity effects by Λ
(Theoretical predictions)

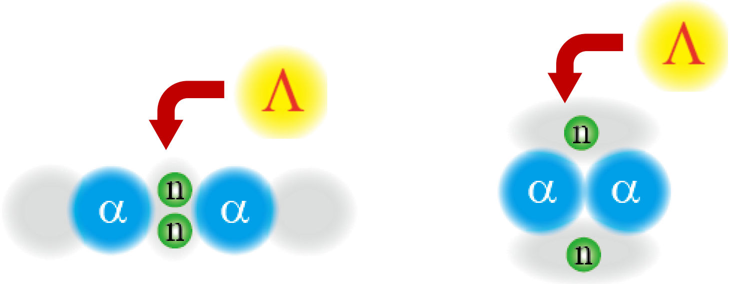
$^{21}_{\Lambda}$Ne **Coexistence of mean-field like and cluster structures**



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

Difference of impurity effects depending on structures

$^{12}_{\Lambda}$Be **Exotic cluster structure of n-rich hypernucleus**



Homma, Isaka, Kimura, PRC**89**,014314(2015)

Using hyperon as a probe to study nuclear structure

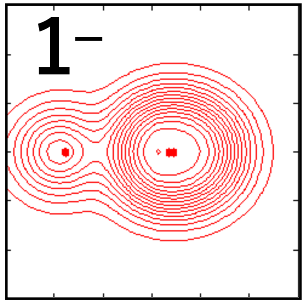
"Overlap between Λ and nucleons" is the key!

Coexistence of mean-field like and cluster structures

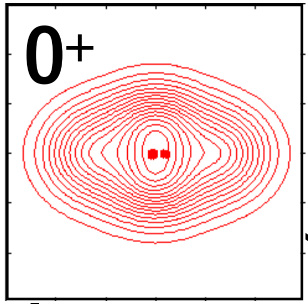
e.g. ^{20}Ne

- **Mean-field like and $\alpha + {}^{16}$O cluster structures coexist within the small excitation energy**

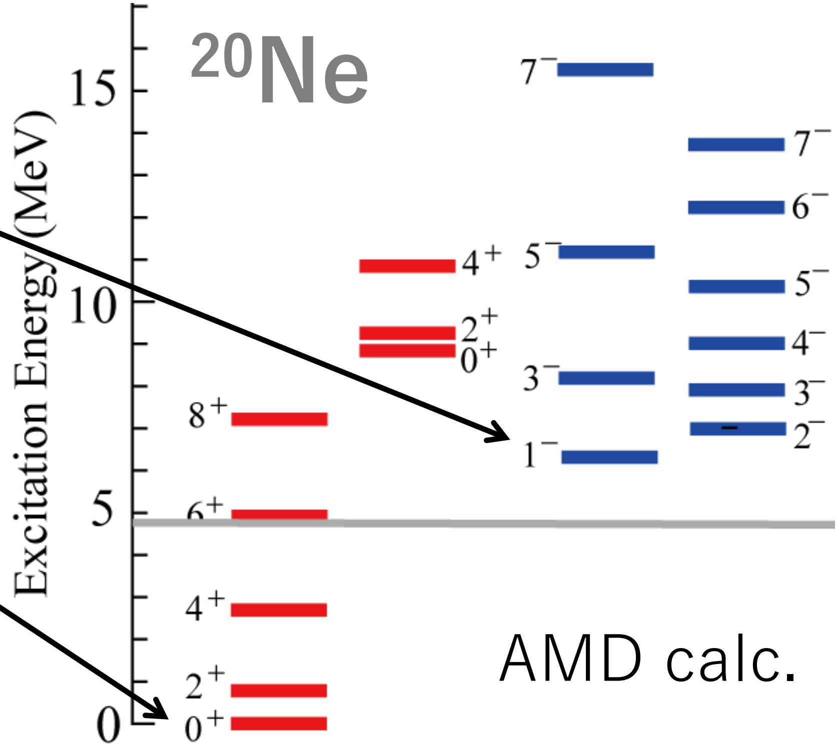
$\alpha + {}^{16}$O



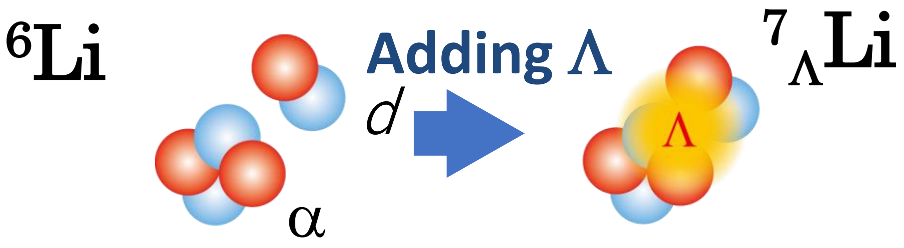
Ground



$\alpha + {}^{16}$O clustering is also mixed



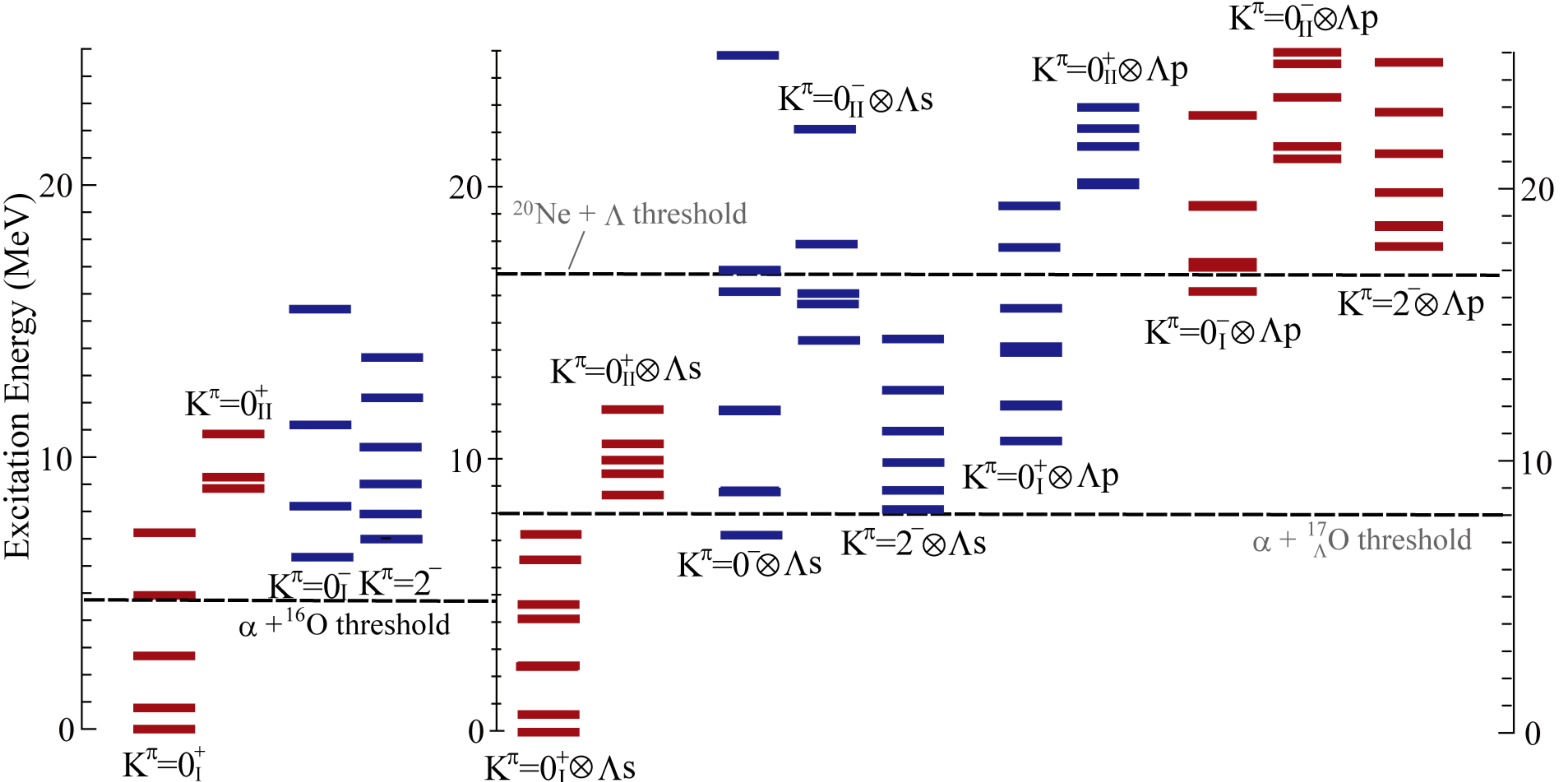
cf. $^{7}_{\Lambda}$Li ($\alpha + d + \Lambda$)



Shrinkage of $\alpha + d$ structure
→ B(E2) reduction

What is difference in structure changes by adding a Λ particle ?
"Λ binding energy (B_Λ)" and "shrinkage"

Results: excitation spectra of $^{21}_{\Lambda}$Ne



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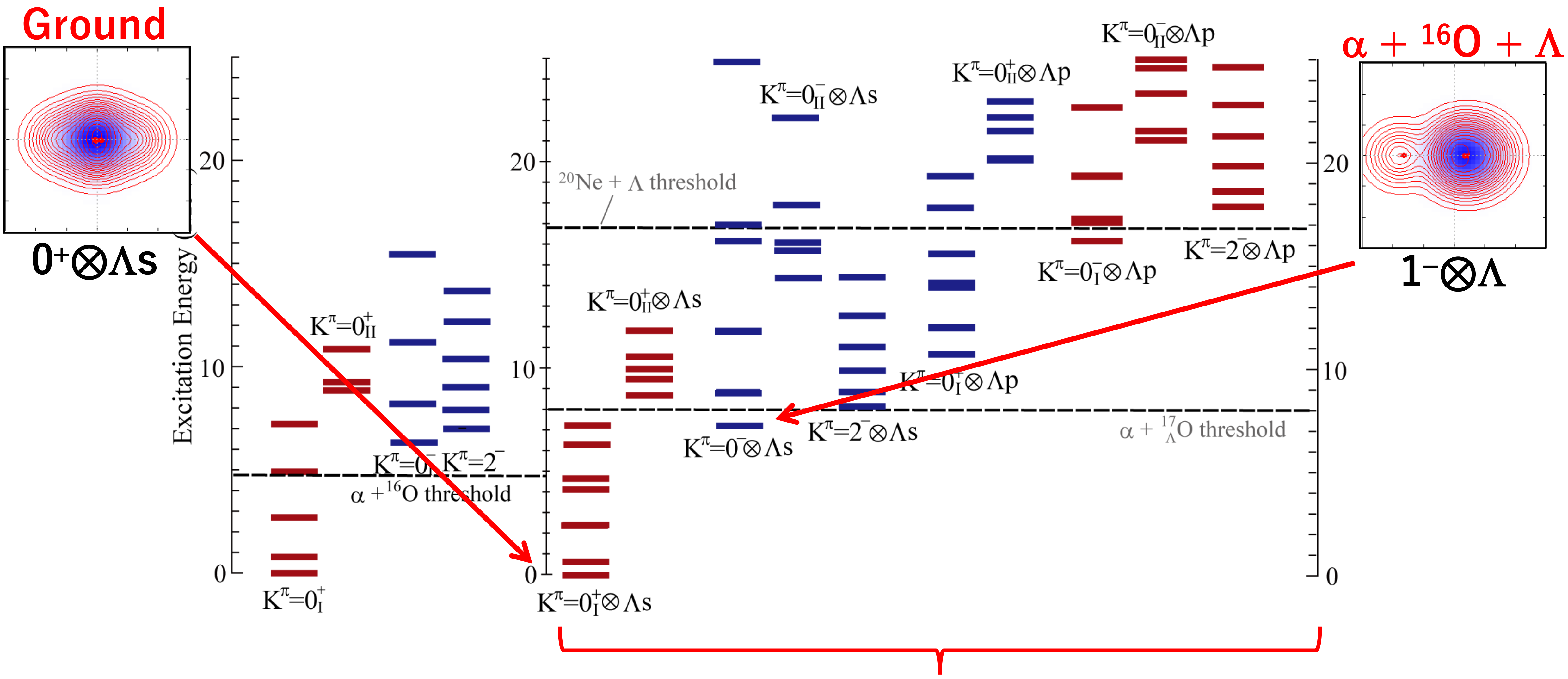
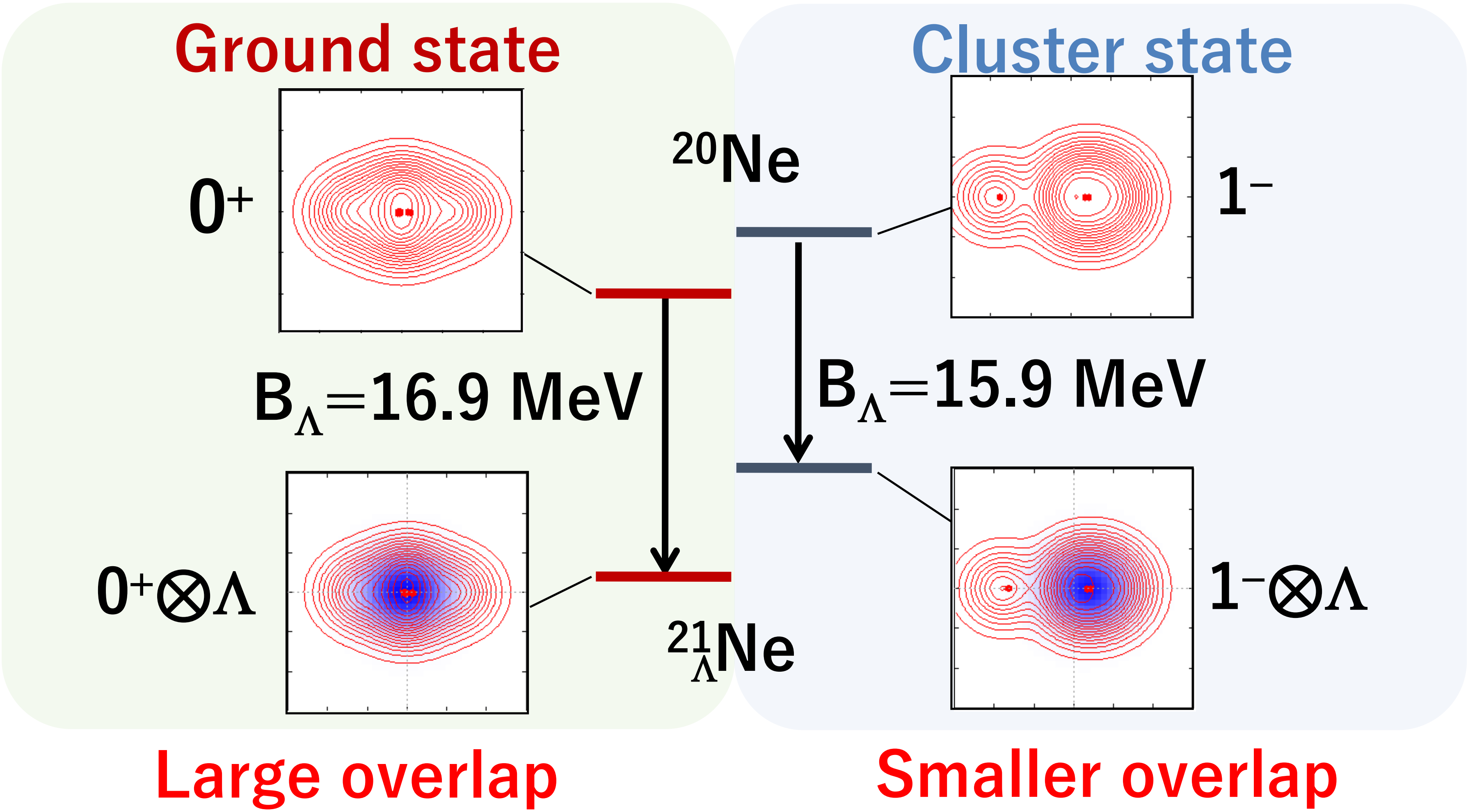


Various states appear by "^{20}Ne$\otimes\Lambda$s" and "^{20}Ne$\otimes\Lambda$p"

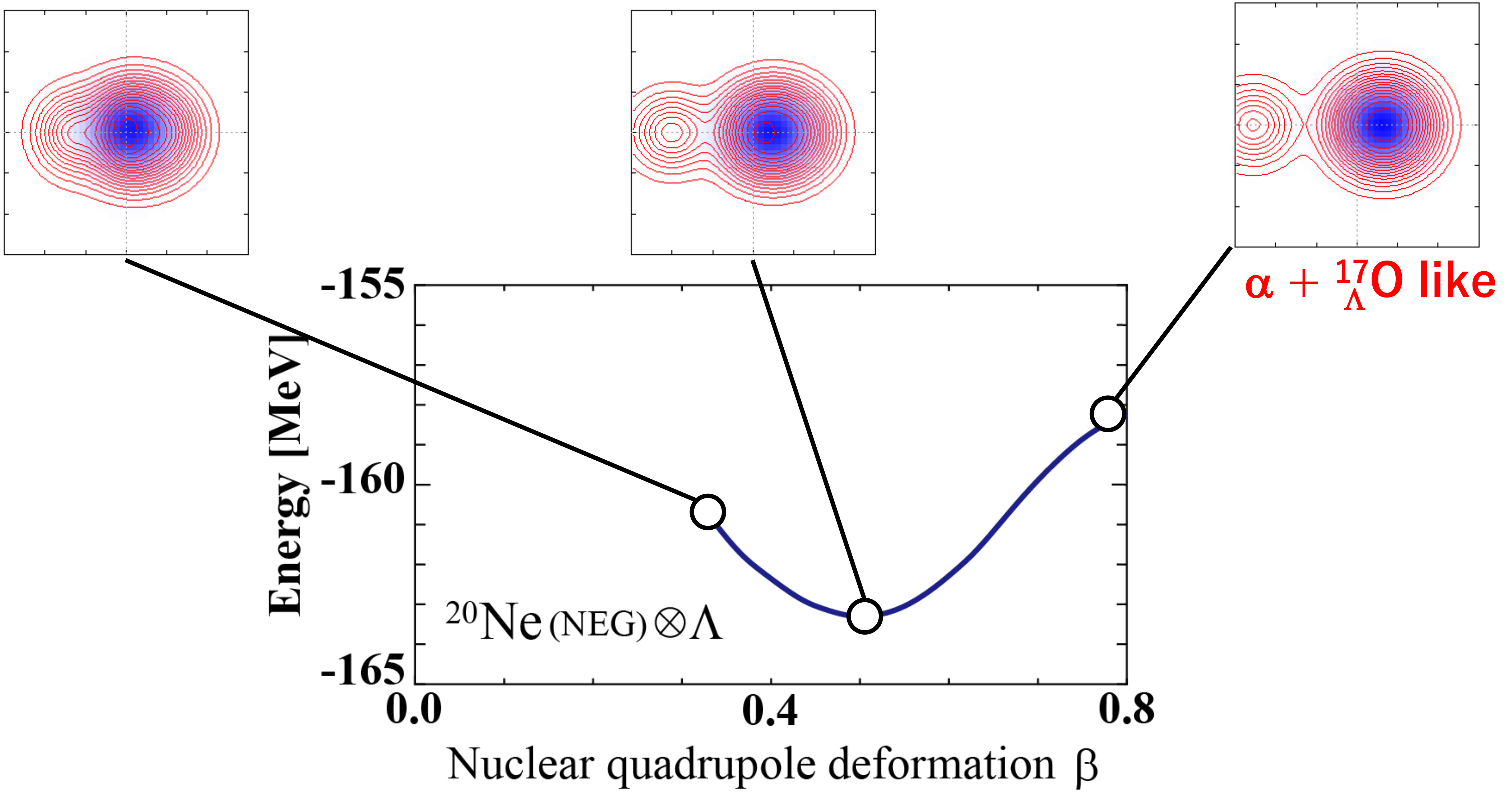
Difference of Λ binding energy B_Λ

- B_Λ is smaller in $\alpha + {}^{16}O + \Lambda$ state than the ground state
- Λ is localized around ^{16}O in $\alpha + {}^{16}O + \Lambda$ cluster state



Localization of Λ in α + ^{16}O + Λ states

- **Λ prefers ^{16}O cluster where Λ is deeply bound than in $^{5}_{\Lambda}$He**



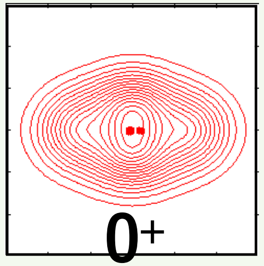
Shrinkage

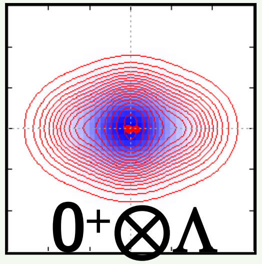
◆Reduction of nuclear r.m.s. radii

●**Shrinkage is larger in the α + ^{16}O + Λ cluster states**

→ **This is mainly due to the reduction of inter-cluster distance**

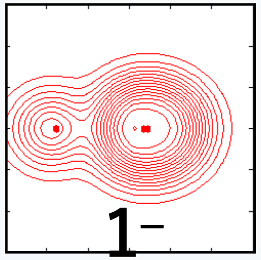
Ground state (Ground band)

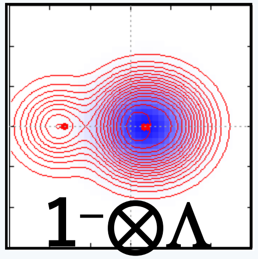




^{20}Ne	r_{RMS}	$^{21}_{\Lambda}$Ne	r_{RMS}	Δr_{RMS}
0+	2.97	(1/2)+	2.92	−0.05
2+	2.96	(3/2)+	2.91	−0.05
		(5/2)+	2.91	−0.05
4+	2.93	(7/2)+	2.87	−0.06
		(9/2)+	2.88	−0.04
6+	2.87	(11/2)+	2.81	−0.05
		(13/2)+	2.83	−0.04
8+	2.82	(15/2)+	2.77	−0.04
		(17/2)+	2.77	−0.05

Cluster states

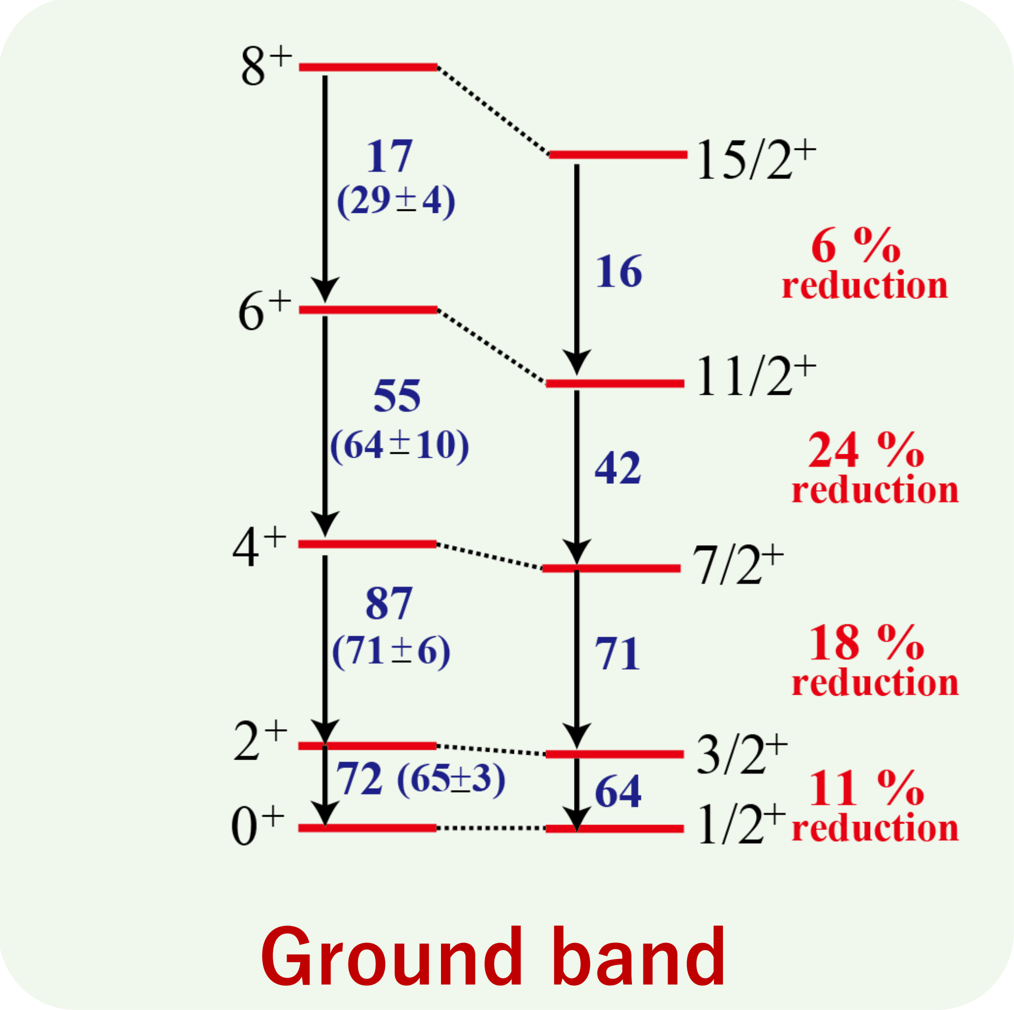


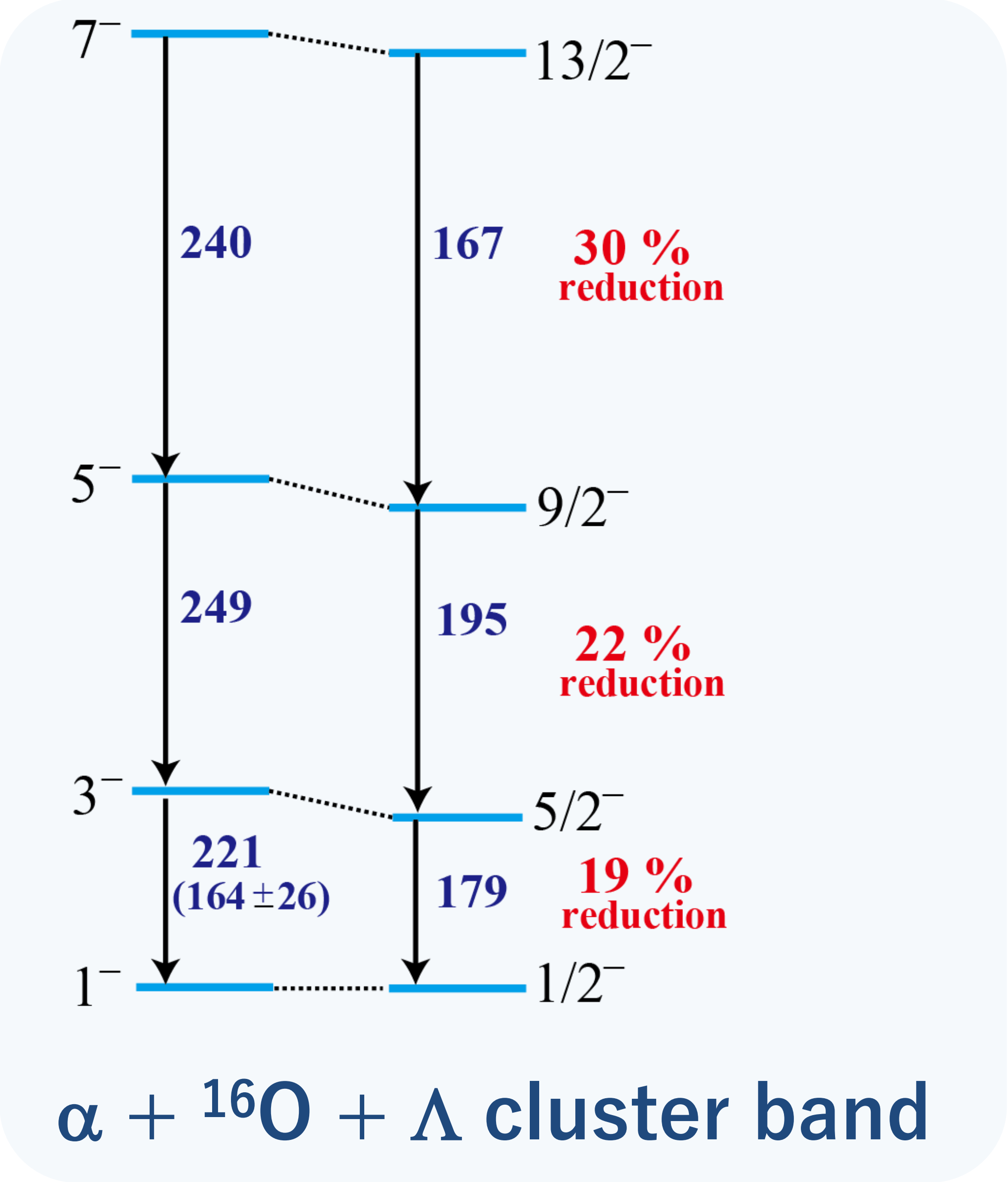


^{20}Ne	r_{RMS}	$^{21}_{\Lambda}$Ne	r_{RMS}	Δr_{RMS}
1−	3.27	(1/2)−	3.15	−0.11
		(3/2)−	3.15	−0.11
3−	3.24	(5/2)−	3.13	−0.11
		(7/2)−	3.14	−0.10
5−	3.23	(9/2)−	3.11	−0.12
		(11/2)−	3.11	−0.13
7−	3.23	(13/2)−	3.06	−0.17
		(15/2)−	3.05	−0.18

Results: B(E2) reduction

◆Intra-band B(E2) values

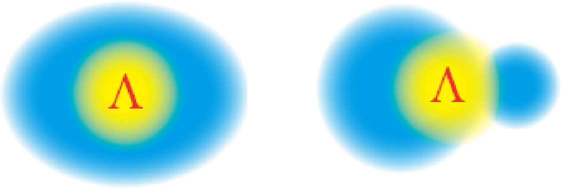




Larger B(E2) reduction in the cluster band

2. Examples of impurity effects by Λ
(Theoretical predictions)

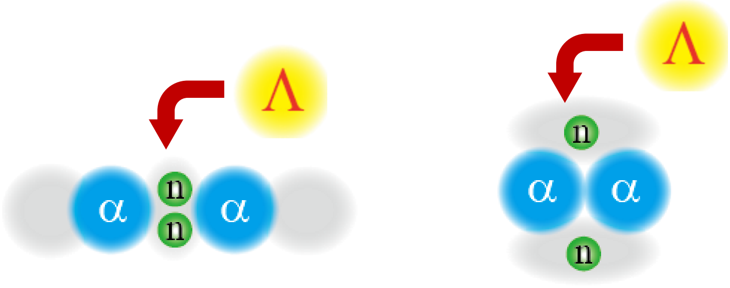
$^{21}_{\Lambda}$Ne **Coexistence of mean-field like and cluster structures**



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

Difference of impurity effects depending on structures

$^{12}_{\Lambda}$Be **Exotic cluster structure of n-rich hypernucleus**



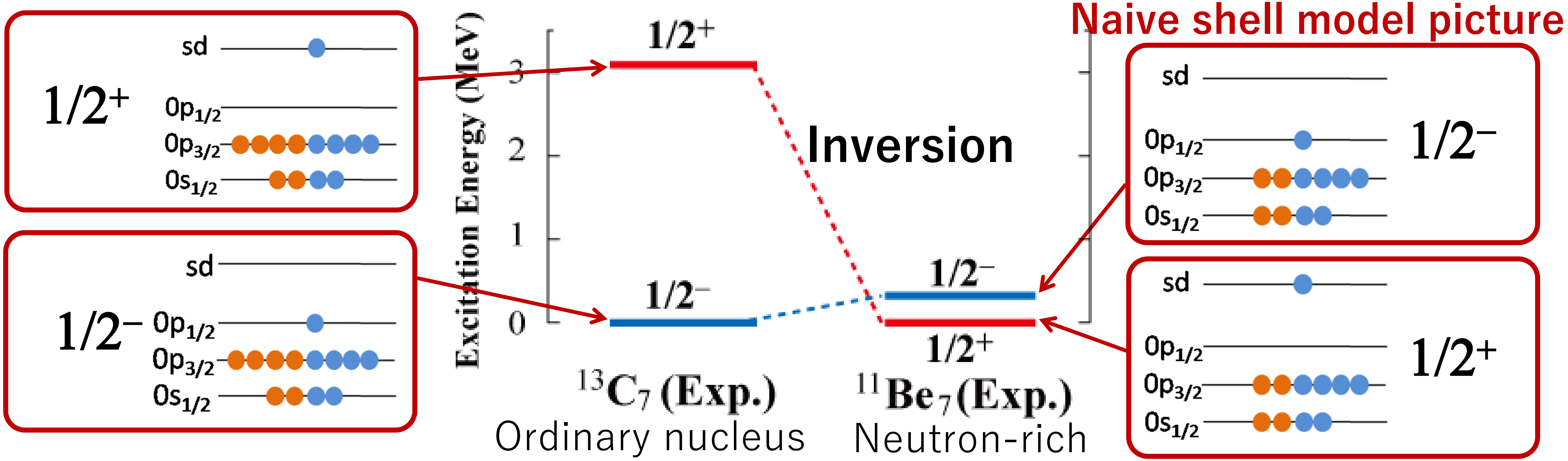
Homma, Isaka, Kimura, PRC**89**,014314(2015)

Using hyperon as a probe to study nuclear structure

"Overlap between Λ and nucleons" is the key!

Example: ^{11}Be with parity-inverted ground state

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



Example: ^{11}Be with parity-inverted ground state

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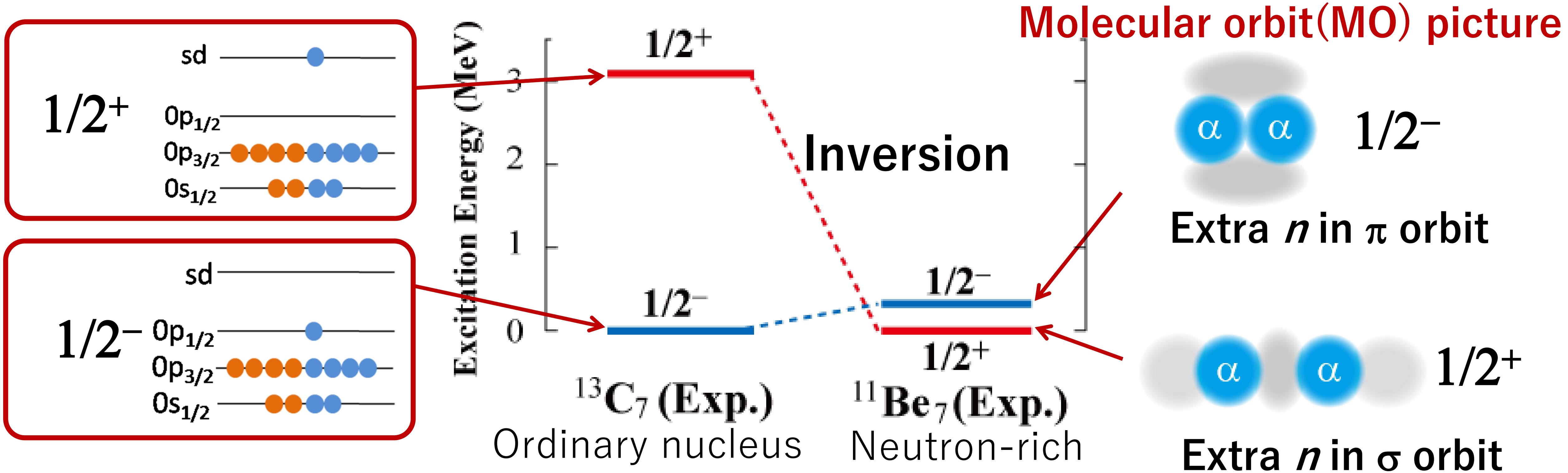

MO explains parity inversion, but difficult to see difference of 2α clustering

⟶ **Λ particle can be a probe to identify the difference**

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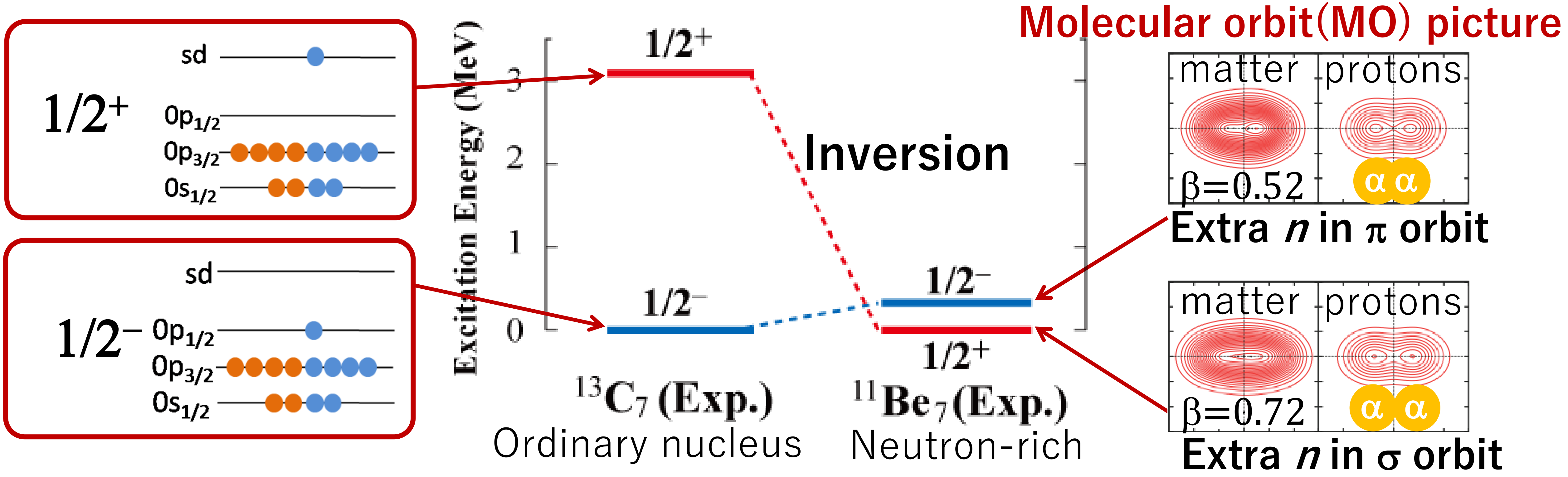
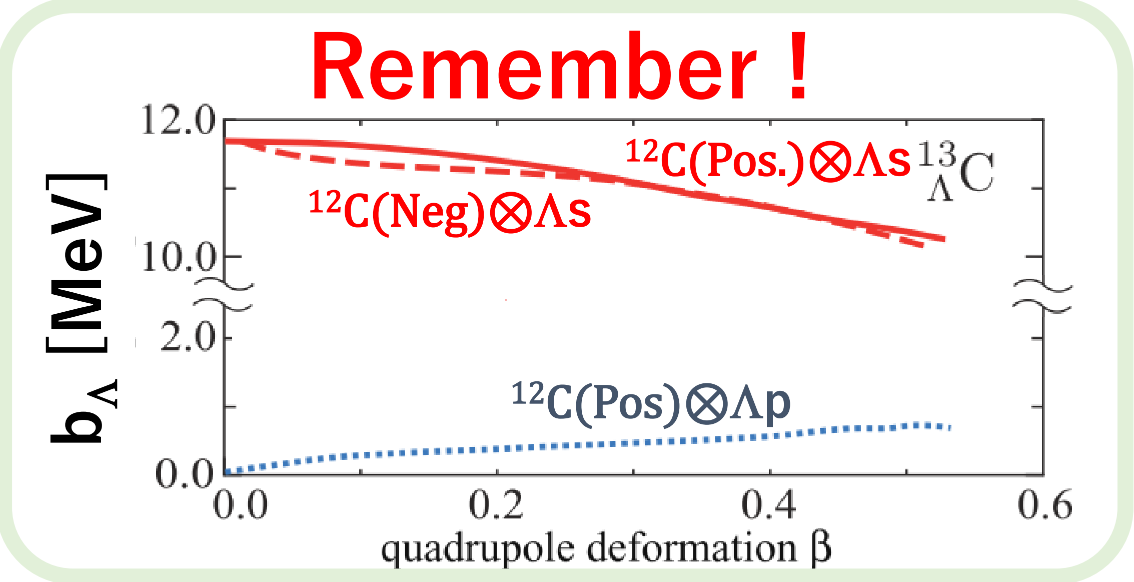


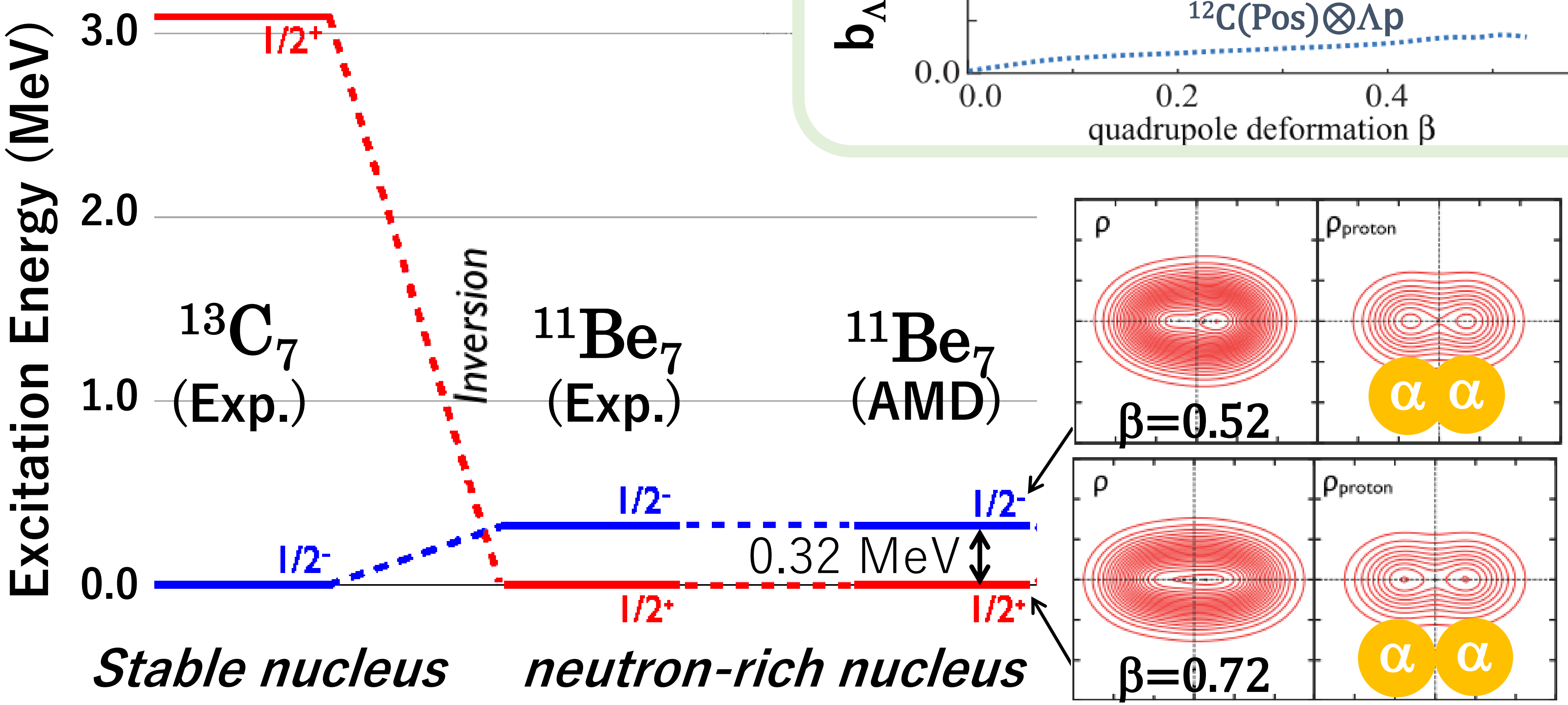
MO explains parity inversion, but difficult to see difference of 2α clustering

⟶ **Λ particle can be a probe to identify the difference**

Expected in $^{12}_{\Lambda}$Be

◆Difference of defromation

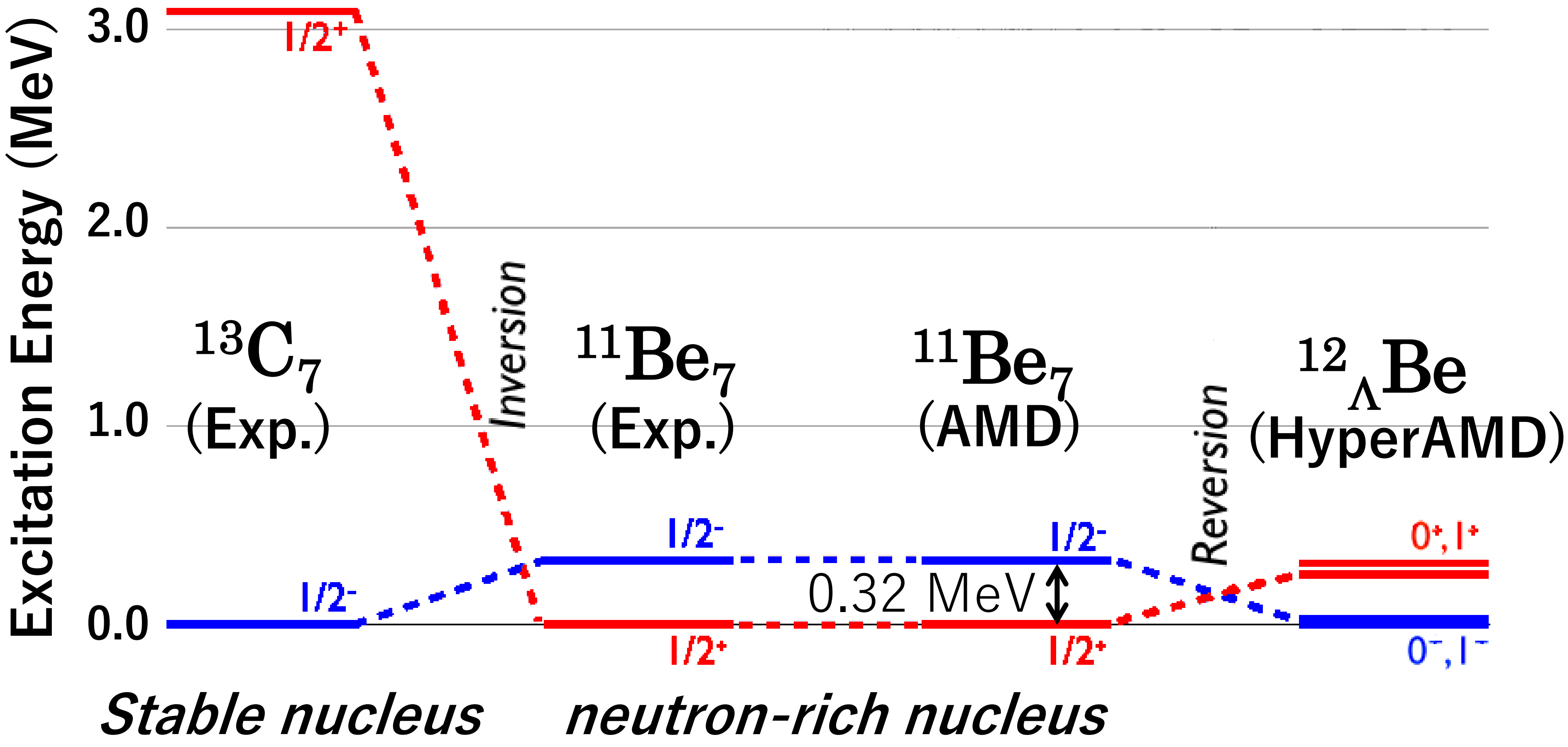




Energy gain of Λ should be different, which causes parity reversion!

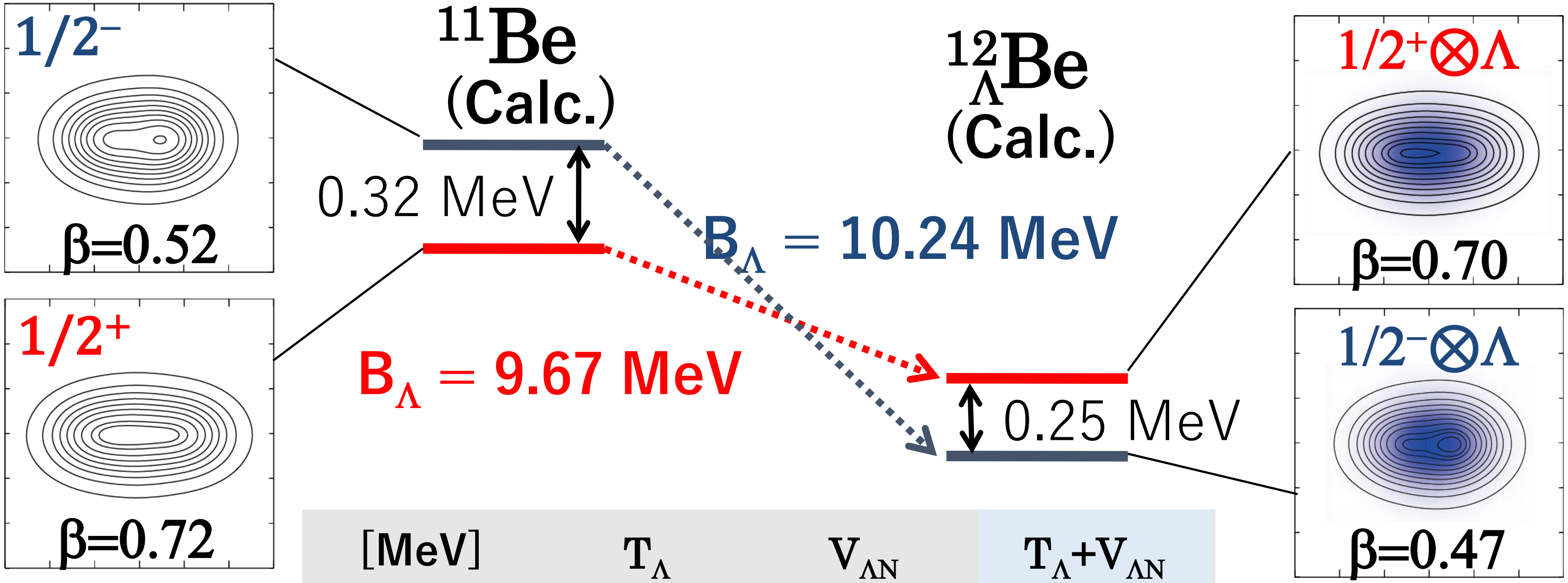
Results: parity reversion of the $^{12}{}_{\Lambda}$Be ground state

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



Parity reversion is predicted by adding a Λ particle

Results: Deformation and Λ binding energy

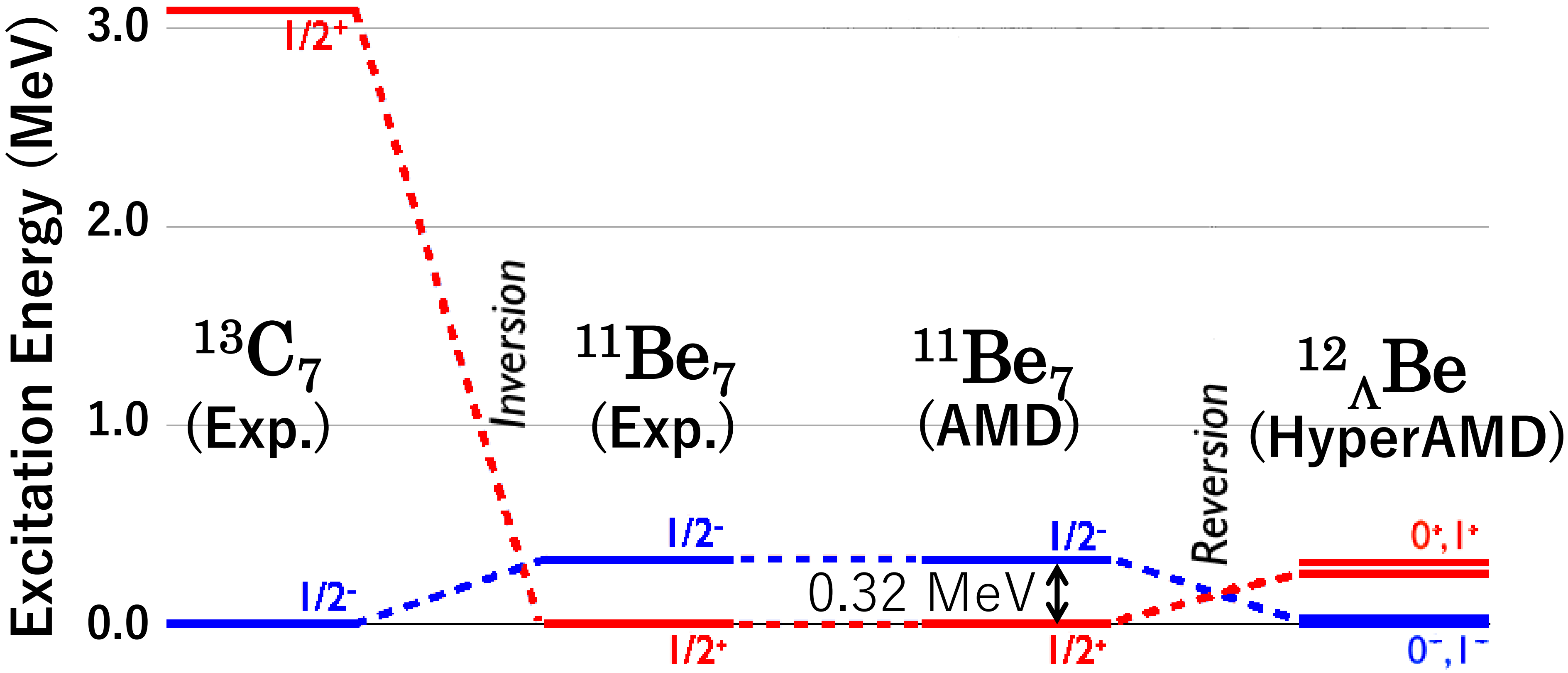


[MeV]	T_Λ	$V_{\Lambda N}$	$T_\Lambda + V_{\Lambda N}$
0_1^-(GS)	6.71	–16.93	–10.22
0_1^+	6.68	–16.42	–9.74

- **Λ slightly reduces deformations, but they are still different**
- **Λ in 1/2⁻ ⊗ Λ state is deeply bound than 1/2⁺ ⊗ Λ state**
  - Due to the difference of the deformation between 1/2⁻ and 1/2⁺

Results: parity reversion of the $^{12}{}_{\Lambda}$Be ground state

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



- Parity reversion due to difference of deformation from 2α clustering
- Difference of 2α clustering can be confirmed from parity reversion

Summary

"Impurity effects": nuclear structure change by a hyperon

● **HyperAMD was applied to several p-sd shell hypernuclei**

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

Deformation changes

- Λ in p orbit enhances the deformation, while Λ in s orbit reduces it

$^{21}{}_{\Lambda}$Ne: Coexistence of structures

- Small B_{Λ} in $\alpha + {}^{16}O + \Lambda$ band related to the localization of Λ
- Larger shrinkage effects in $\alpha + {}^{16}O + \Lambda$ band and B(E2) reduction

$^{12}{}_{\Lambda}$Be: Λ as a probe to investigate difference of cluster structure

- Parity-inverted ground state of ^{11}Be is reverted in $^{12}{}_{\Lambda}$Be

◆Future works

● **Impurity effects & structure study of hypernuclei**

e.g. $^{19}{}_{\Lambda}$F, K hypernuclei, hypernuclei in *p*-shell mass regions