Structure of hypernuclei:

What will happen by the coupling of a Λ particle?

Masahiro Isaka, Hosei University

Hypernuclei

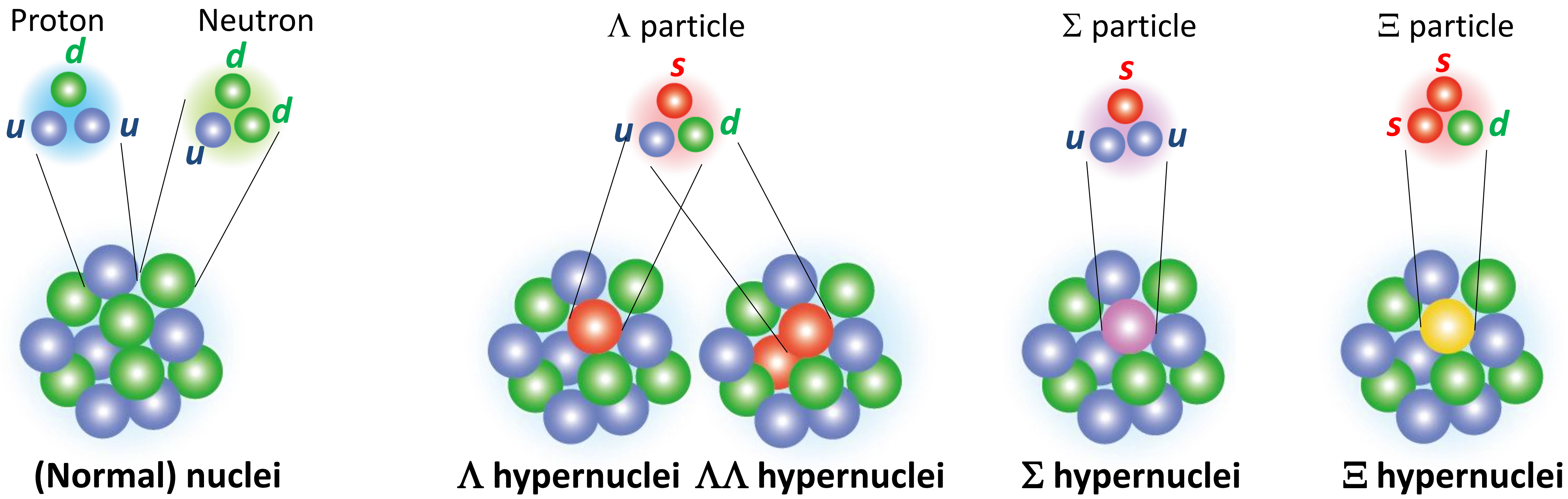
◆Normal nuclei

- **Nucleons**
  - protons & neutrons

◆Hypernuclei

- **Nucleons and hyperon(s) (Λ, Σ, Ξ)**
- **Several kinds of hypernuclei exist**

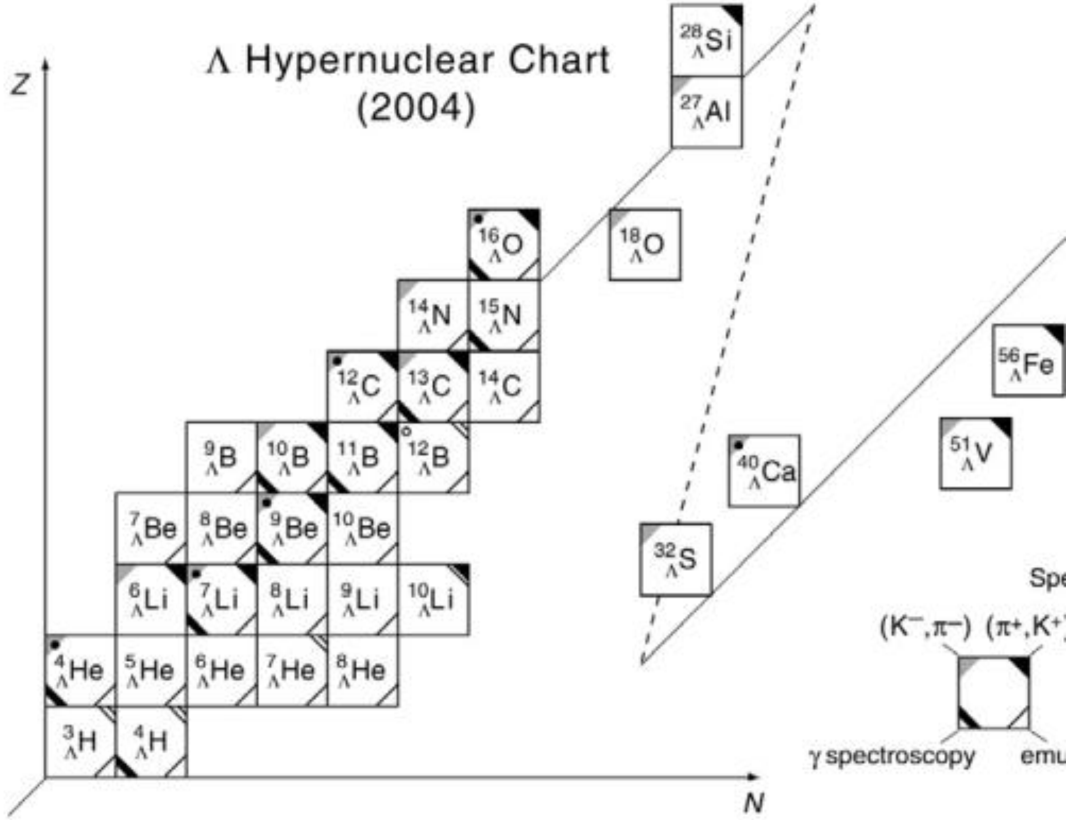
→ **Today's talk: single Λ hypernuclei**



Current situation of Λ hypernuclear studies

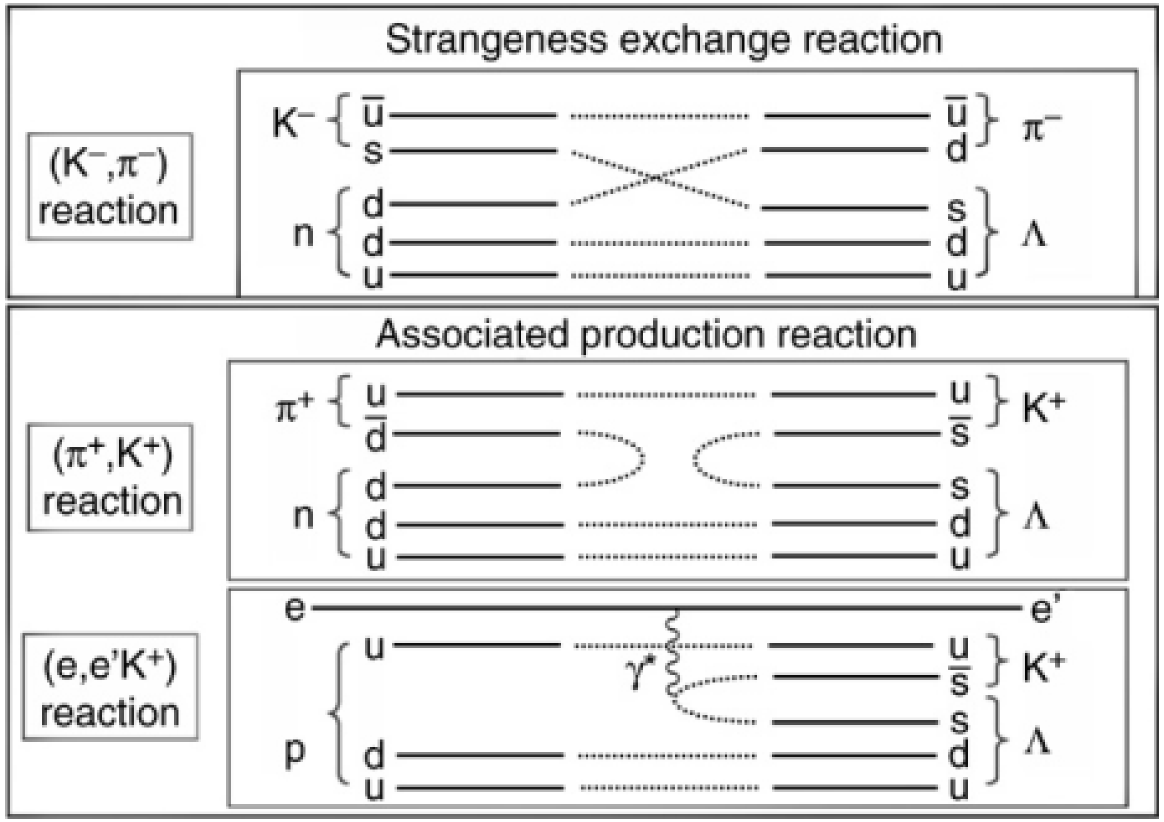
Hashimoto & Tamura, PPNP **57** (2006), 564.

Hypernuclei observed so far



Now, Λ hypernuclear chart is extended more!

Production process of Λ hypernuclei

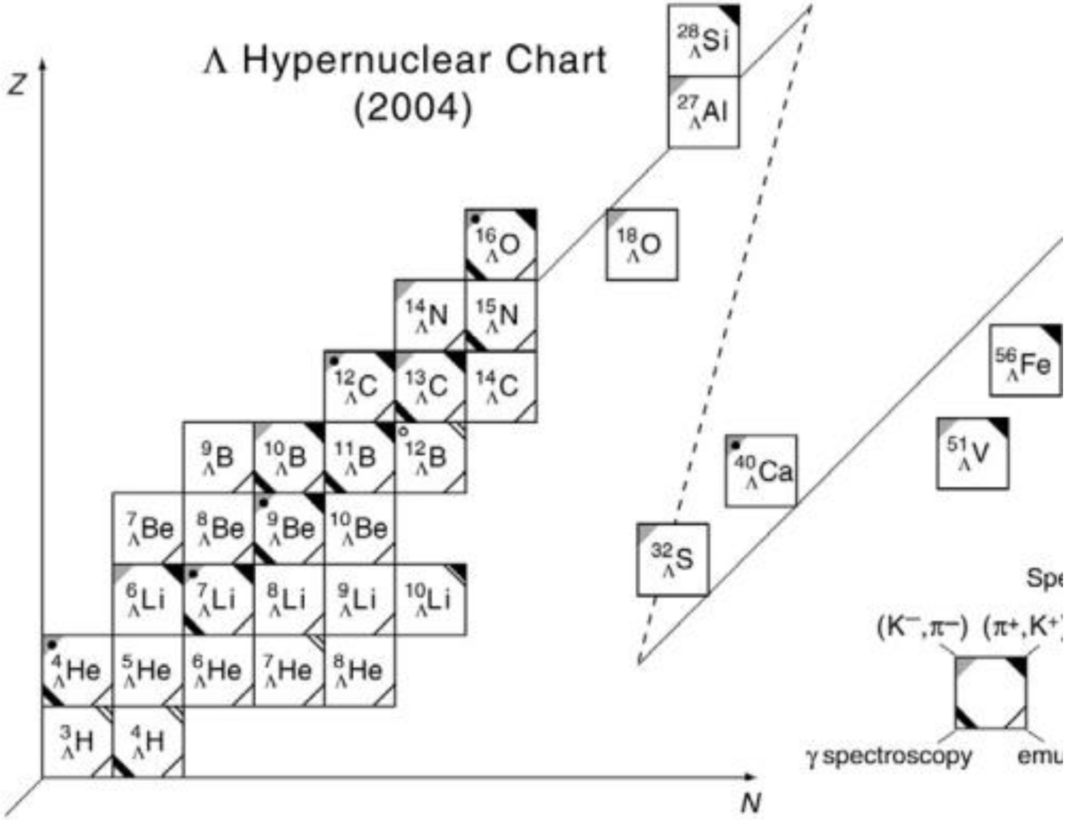


and Λ hypernuclear production by heavy ion collisions, etc.

Current situation of Λ hypernuclear studies

Hashimoto & Tamura, PPNP **57** (2006), 564.

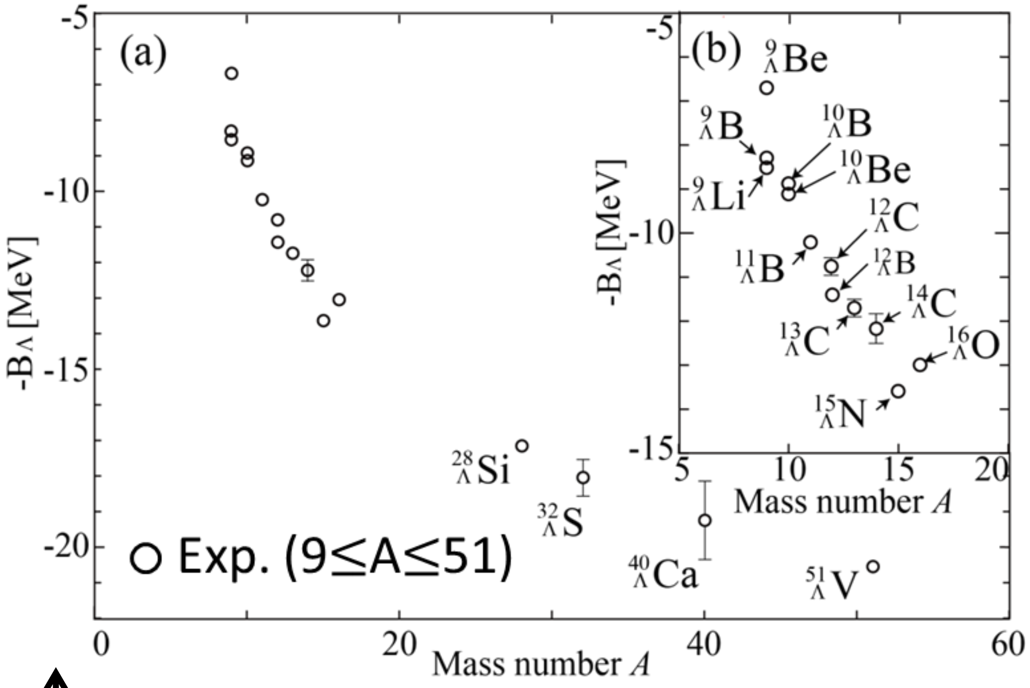
Hypernuclei observed so far



Now, Λ hypernuclear chart is extended more!

Observed data: Λ binding energy B_Λ

A most basic and important quantity



E

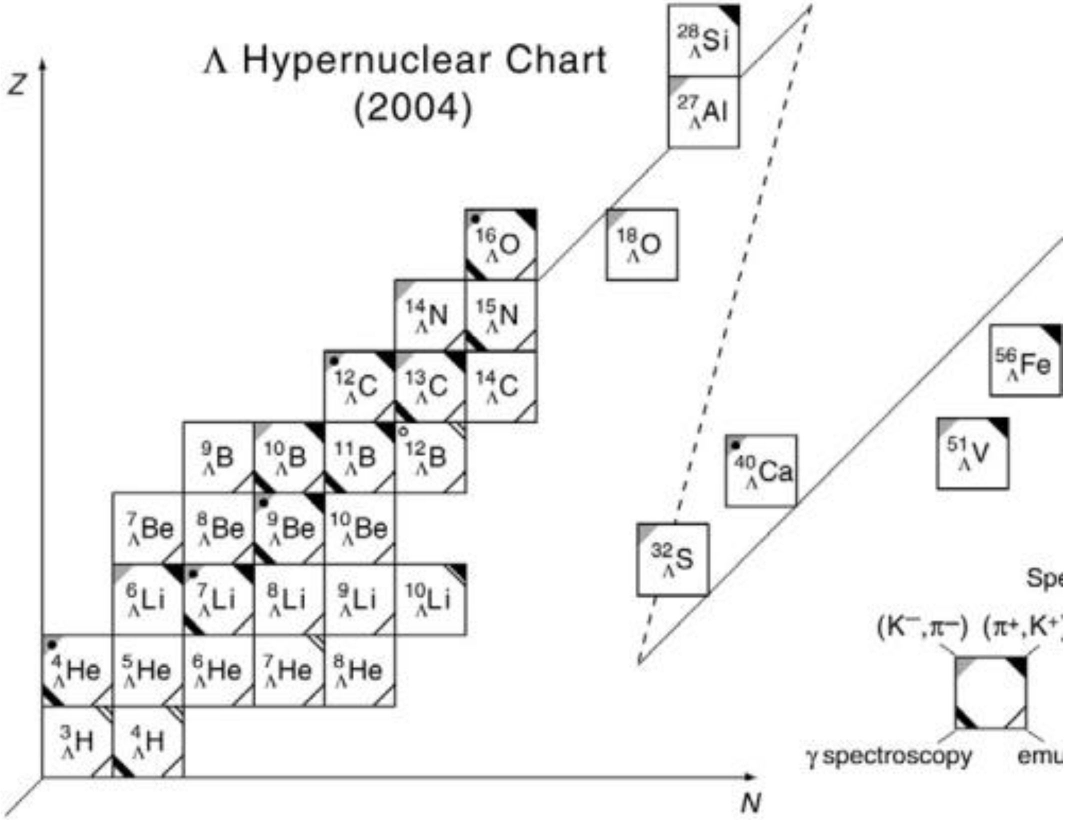
Energy of the core nuclei ^{A}Z

B_Λ: energy gain by a Λ particle

E of corresponding hypernucleus $^{A+1}{}_{\Lambda}Z$

Current situation of Λ hypernuclear studies

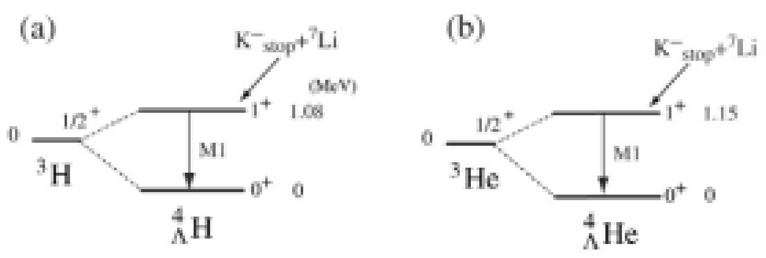
Hypernuclei observed so far



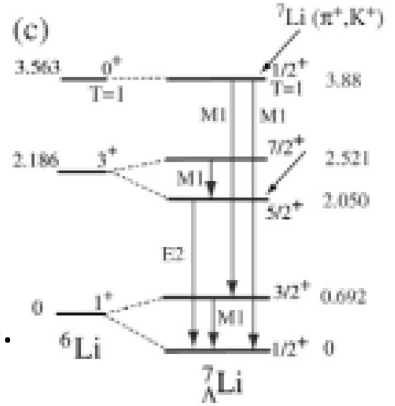
Now, Λ hypernuclear chart is extended more!

Observed data: Excited states

γ-ray spectroscopy data for bound states



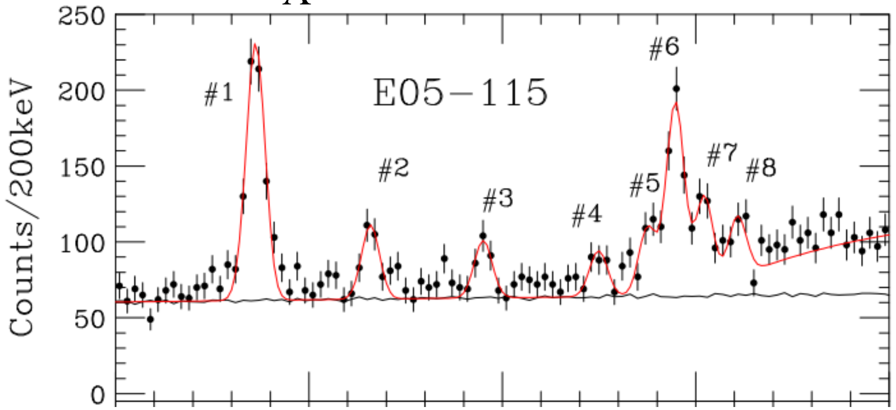
Hashimoto & Tamura, PPNP **57** (2006), 564.



(e,e'K⁺) reaction spectroscopy at JLab :

not only bound but also unbound states

e.g. ^{12}C(e,e'K⁺)$^{12}{}_{\Lambda}$B L. Tang, et al.,PRC**90**, 034320(2014)



Grand challenges of hypernuclear physics

Interaction: To understand baryon-baryon interaction

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

  → **Studied through hypernuclei due to difficulty of YN scattering exp.**

- Many-body interaction

  → **Important issue in recent studies**

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

Many-body force and "Hyperon puzzle" in neutron star

Hyperon puzzle

Massive $(2M_{\odot})$ neutron stars

2010 PSR J1614-2230 $(1.97 \pm 0.04) M_{\odot}$

2013 PSR J0348-0432 $(2.01 \pm 0.04) M_{\odot}$

?

Softening of EOS by hyperon mixing

How do we resolve?

Baryon many(three)-body force

If strong repulsion exists acting in hyperonic channels,
EOS of neutron star matter becomes stiff

Important issue in hypernuclear physics:
to reveal effects of hyperonic many-body force in Λ hypernuclei

Grand challenges of hypernuclear physics

Interaction: To understand baryon-baryon interaction

- **2 body interaction between baryons (Y: hyperon, N: nucleon): YN, YY interactions**
  → **Studied through hypernuclei due to difficulty of YN scattering exp.**
- **Many-body interaction**
  → **Important issue in recent studies**

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

- **Addition of 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 nuclear force

} Hyperon as an impurity in hypernuclei

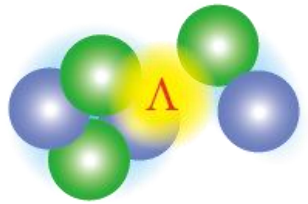
Structure of Λ hypernuclei

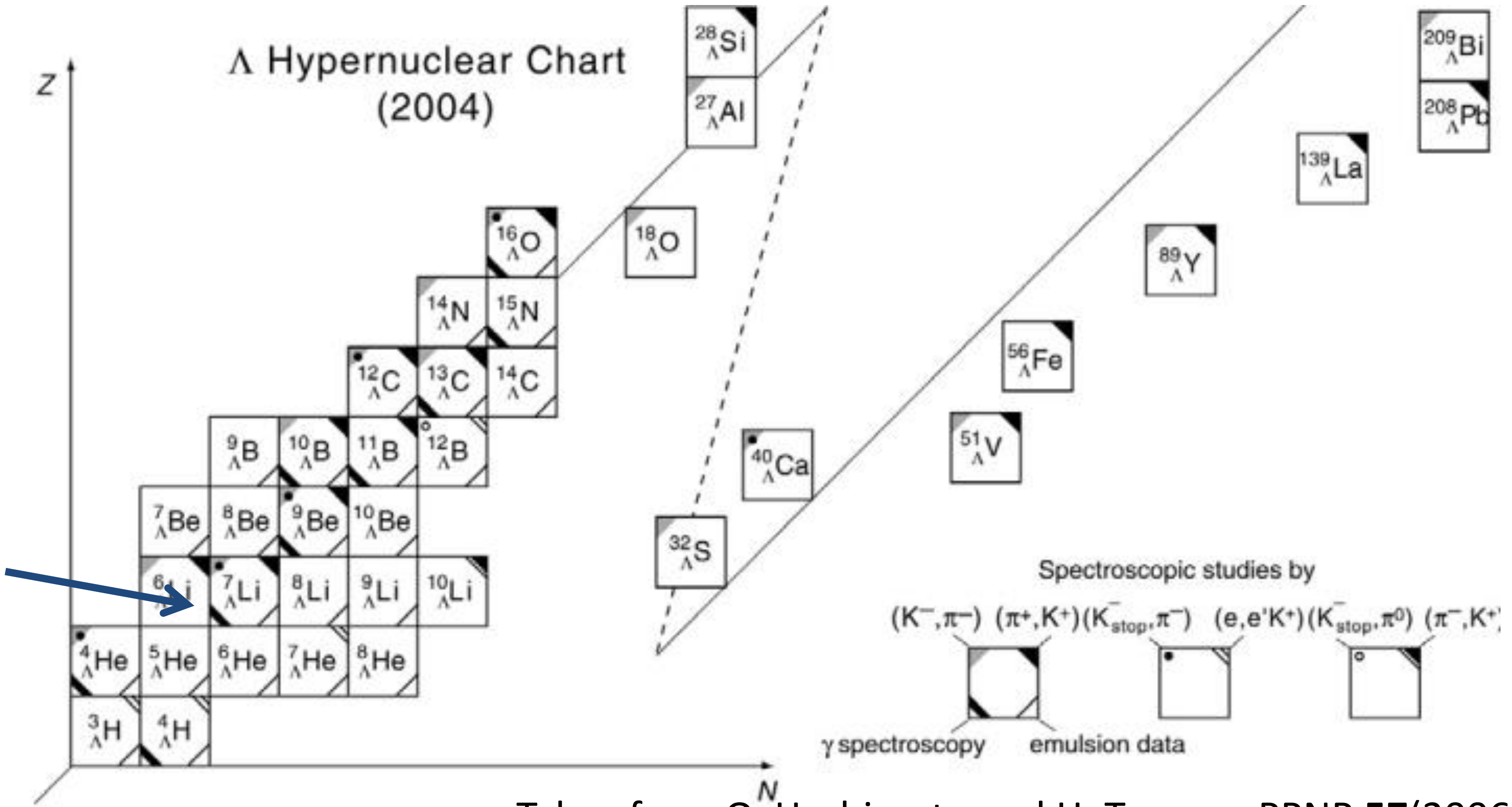
◆ Λ hypernuclei observed so far

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

Light Λ hypernuclei

Developed cluster





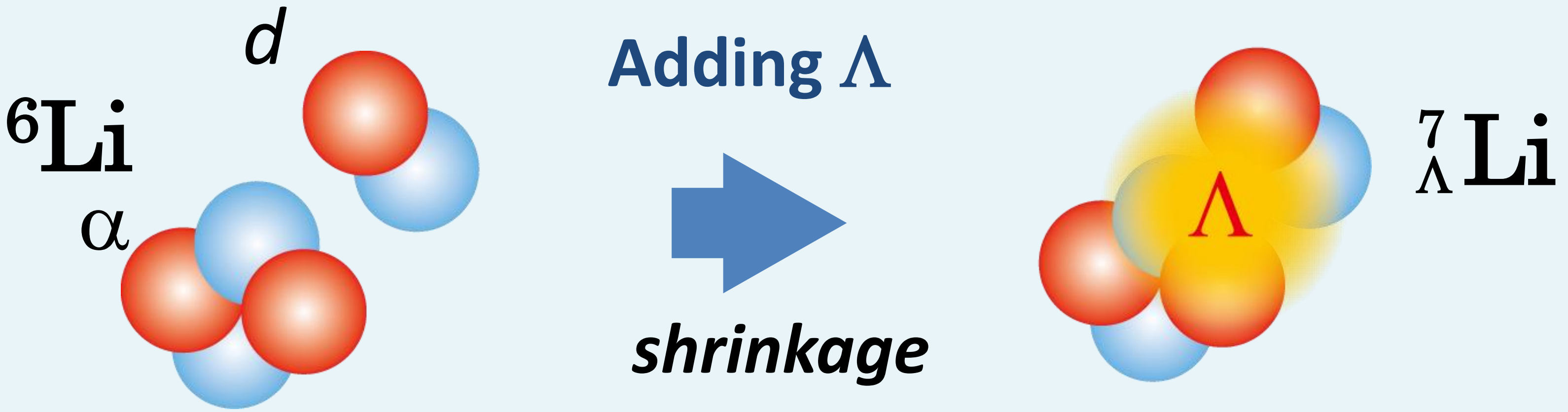
Taken from O. Hashimoto and H. Tamura, PPNP **57**(2006),564.

Cluster structure in light hypernuclei

◆Famous example of "impurity effects"

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.

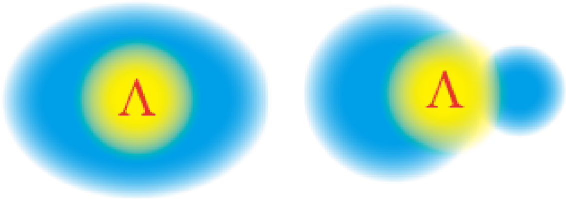


- Λ reduces inter-cluster distance b/w α + *d* of the core nucleus ^{6}Li
- Confirmed through B(E2) reduction

Toward heavier and exotic Λ hypernuclei

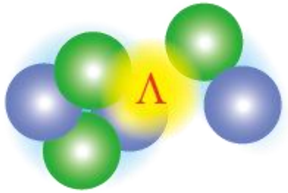
- **Experiments at JLab, J-PARC, … *etc.***
  - **Heavier(*sd*-shell and more) hypernuclei can be produced**

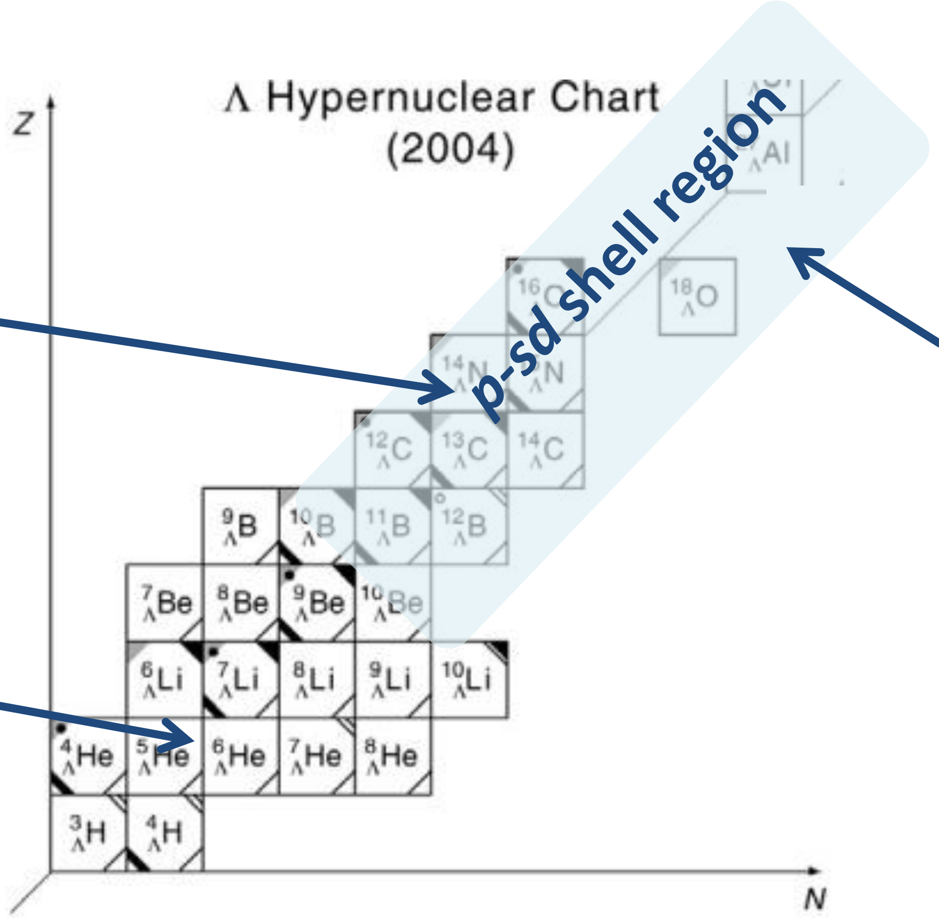
Coexistence of structures



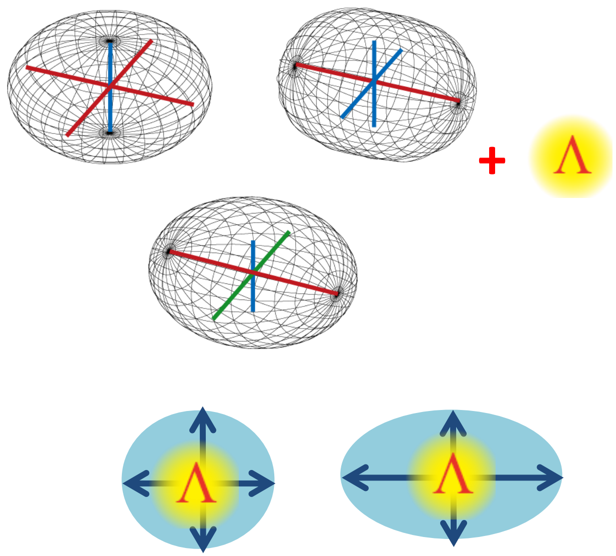
Light Λ hypernuclei

Developed cluster





Various deformations

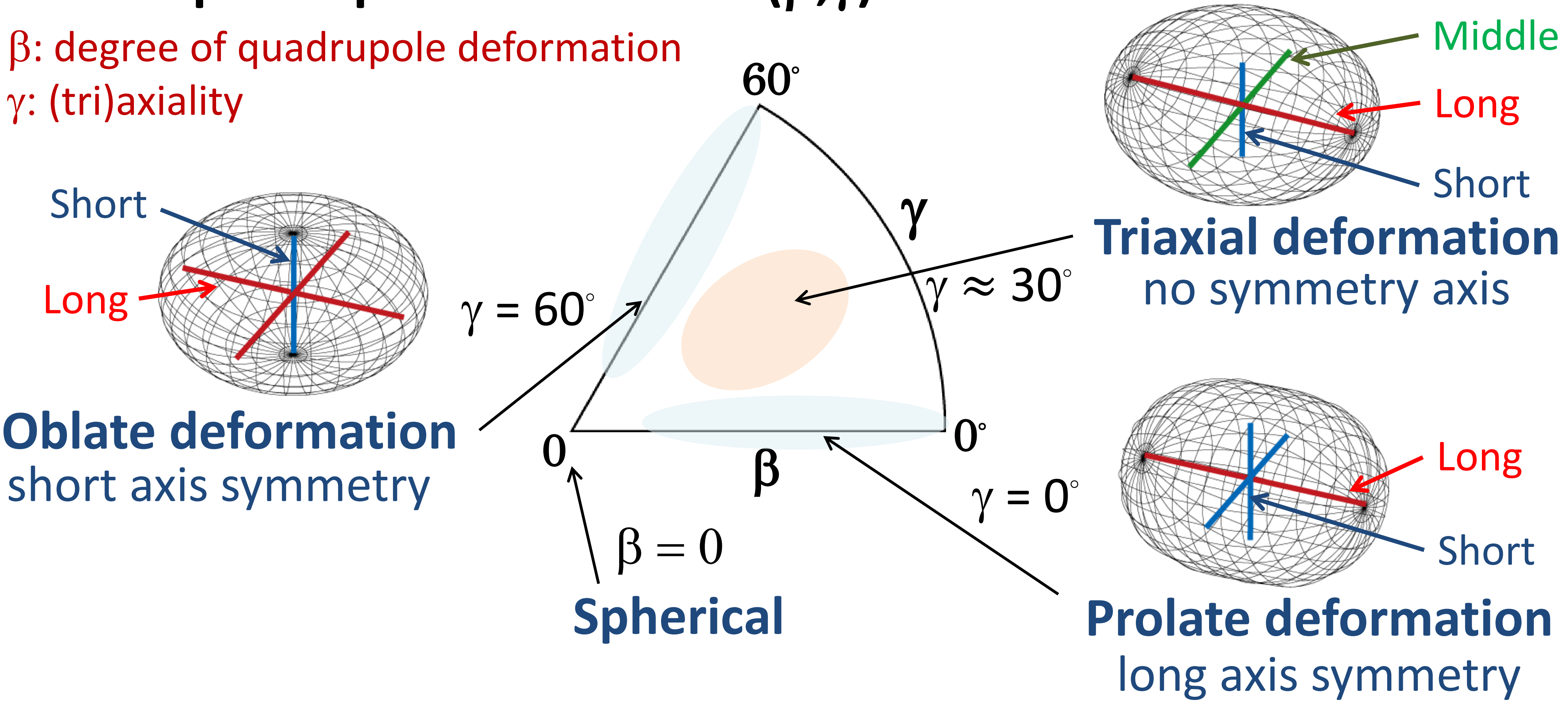


What will happen if a Λ is coupled to nuclei with various structures ?

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



Deformation of nuclei

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- β: degree of quadrupole deformation
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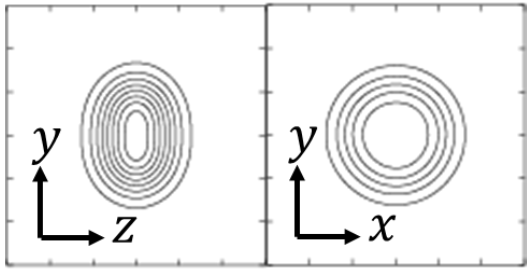
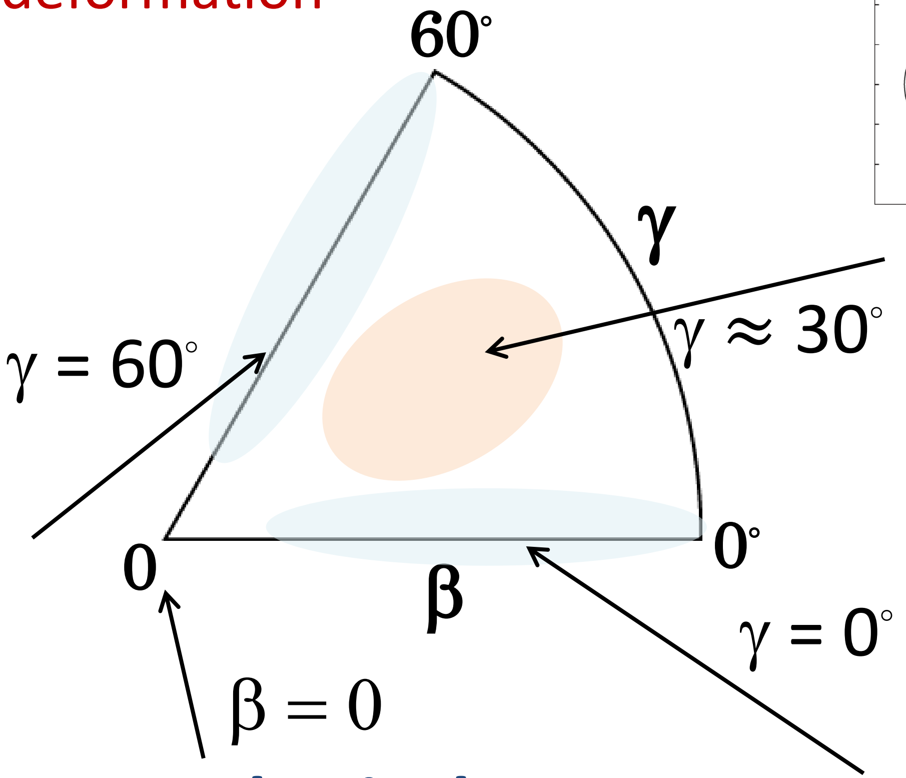
^{12}C

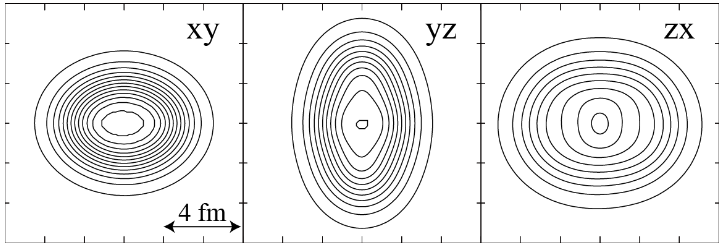


Oblate deformation
short axis symmetry



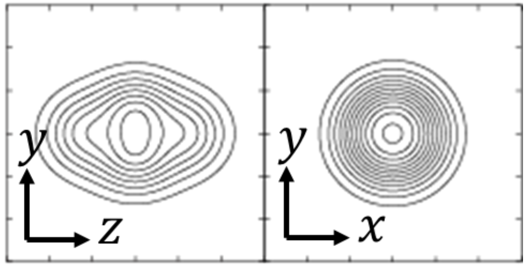
Spherical

^{26}Mg



Triaxial deformation
no symmetry axis

^{20}Ne



Prolate deformation
long axis symmetry

Density distribution with AMD calc

What will happen if a Λ particle is coupled to nuclei ?

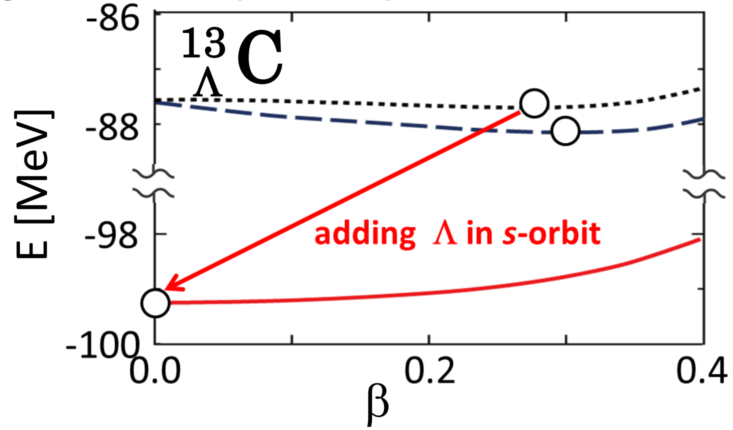
- **Dynamical changes of nuclear structure**
  - Changes of cluster structure
  - Deformation changes
- **Sensitivity of the Λ binding energy B_Λ on nuclear structure**
  - Dependence of B_Λ on nuclear deformation
  - Mass number A dependence & many-body force effects
- **Coupling of Λ particle in *p* orbit to clustering/deformed core nuclei**
  - Genuine hypernuclear states
  - Possibility to probe nuclear deformation using Λ particle

Deformation change by Λ particle

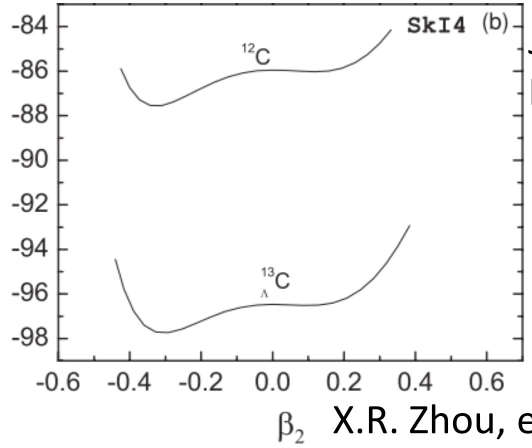
Many authors predict that Λ in *s*-orbit reduces nuclear deformation

Antisymmetrized molecular Dynamics (AMD)

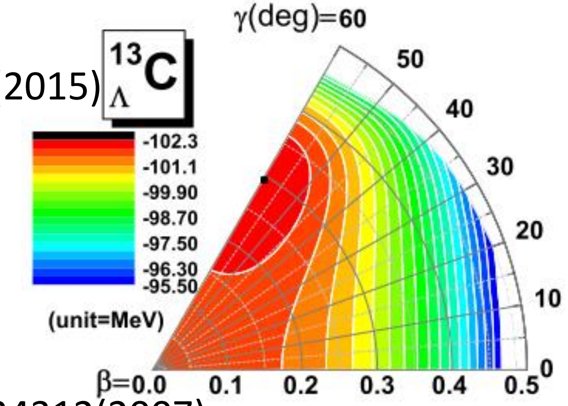
M.I, et al., PRC**83**, 044323(2011)



Skyrme-Hartree-Fock (SHF)



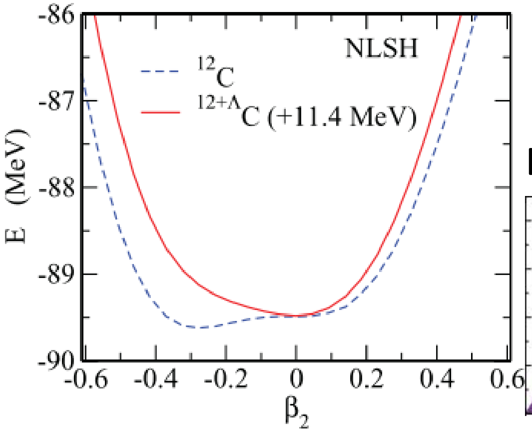
J.W. Cui, et al, PRC**91**,054306(2015)



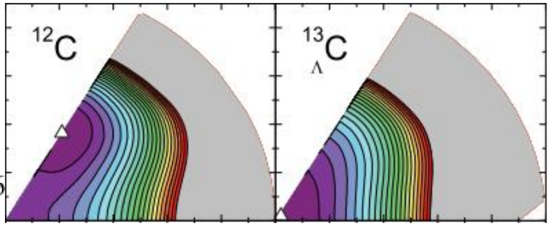
X.R. Zhou, et al., PRC**76**, 034312(2007)

Relativistic mean-field (RMF)

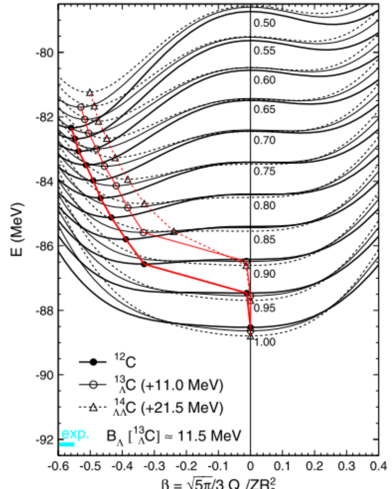
Win and Hagino, PR C**78**, 054311(2008)



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

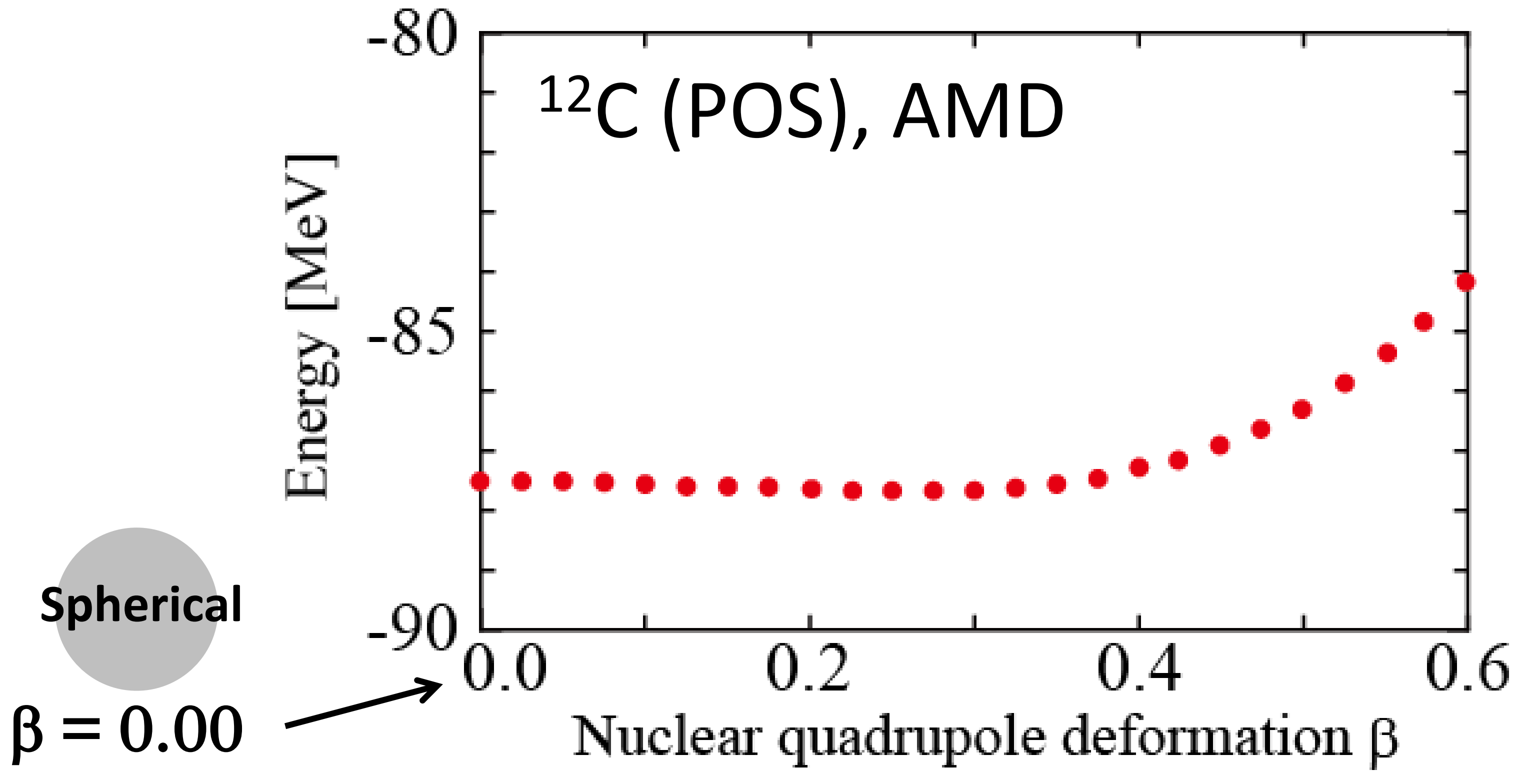
Deformation change by Λ particle

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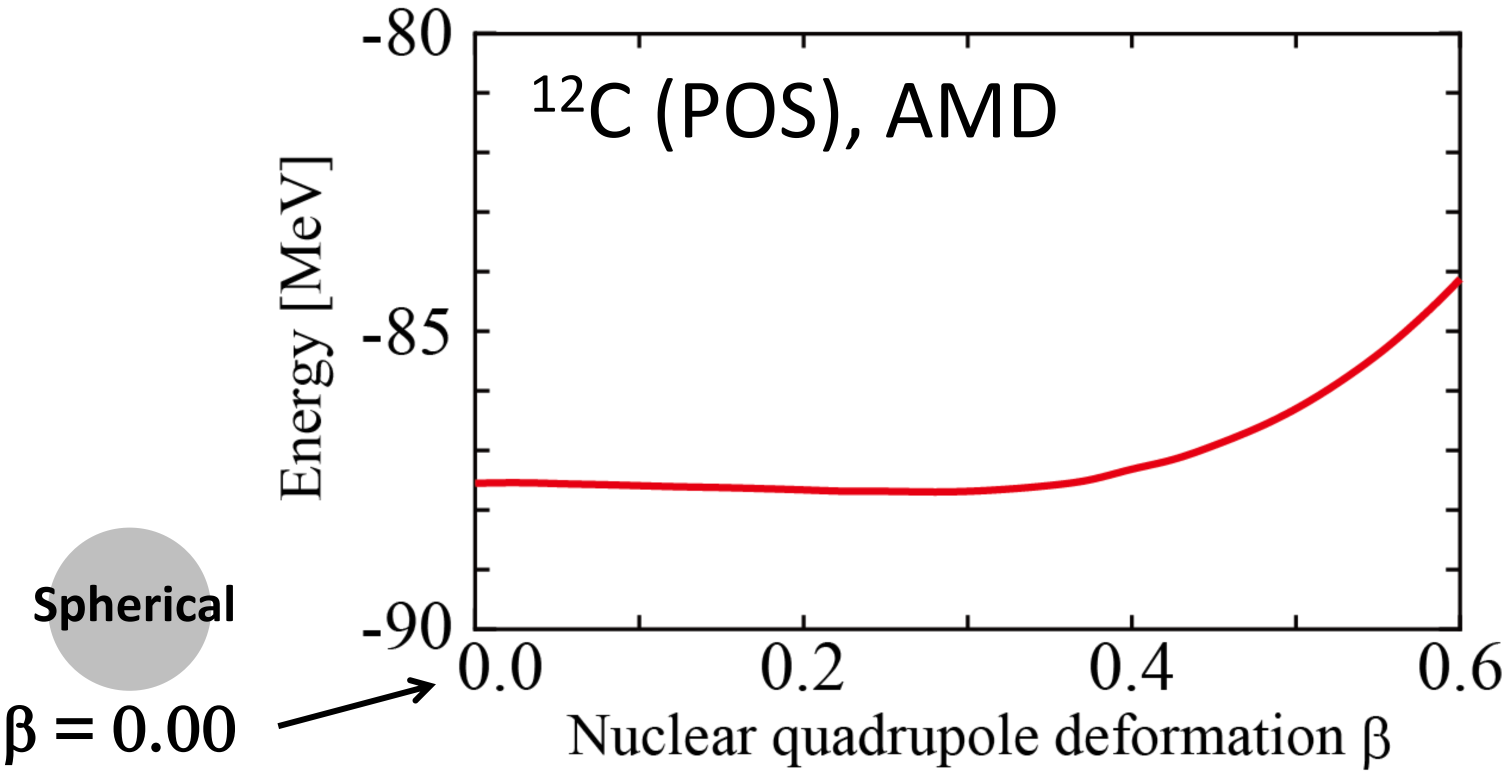
M.I, et al., PRC**83**, 044323(2011)



Deformation change by Λ particle

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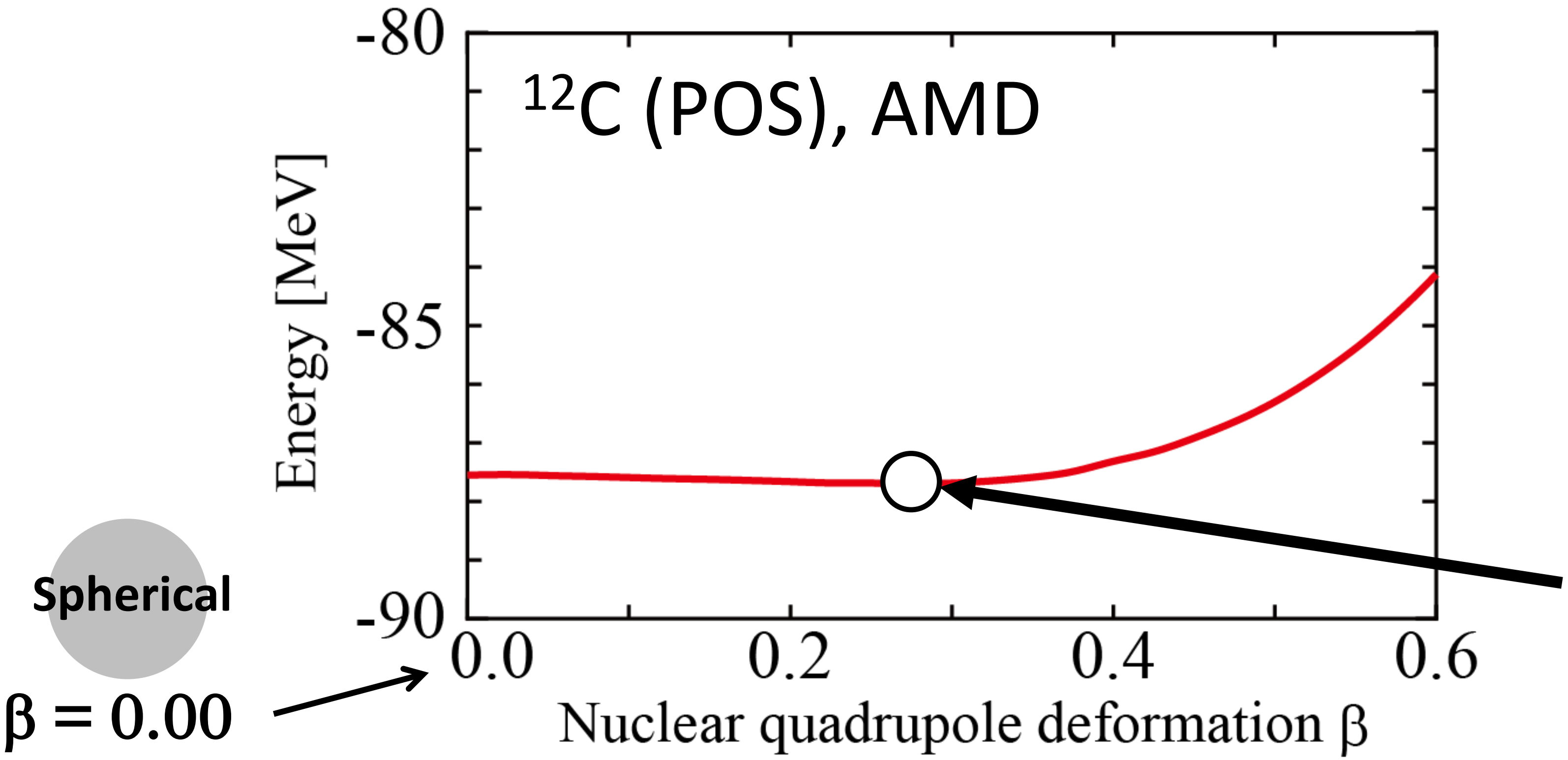
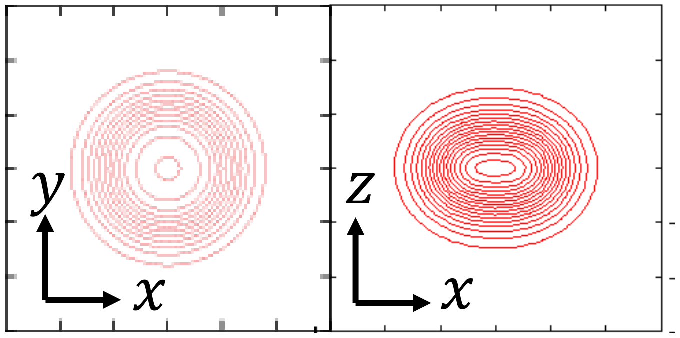
M.I, et al., PRC**83**, 044323(2011)



Energy minimum



β = 0.27, γ = 60°

Deformation change by Λ in *s*-orbit

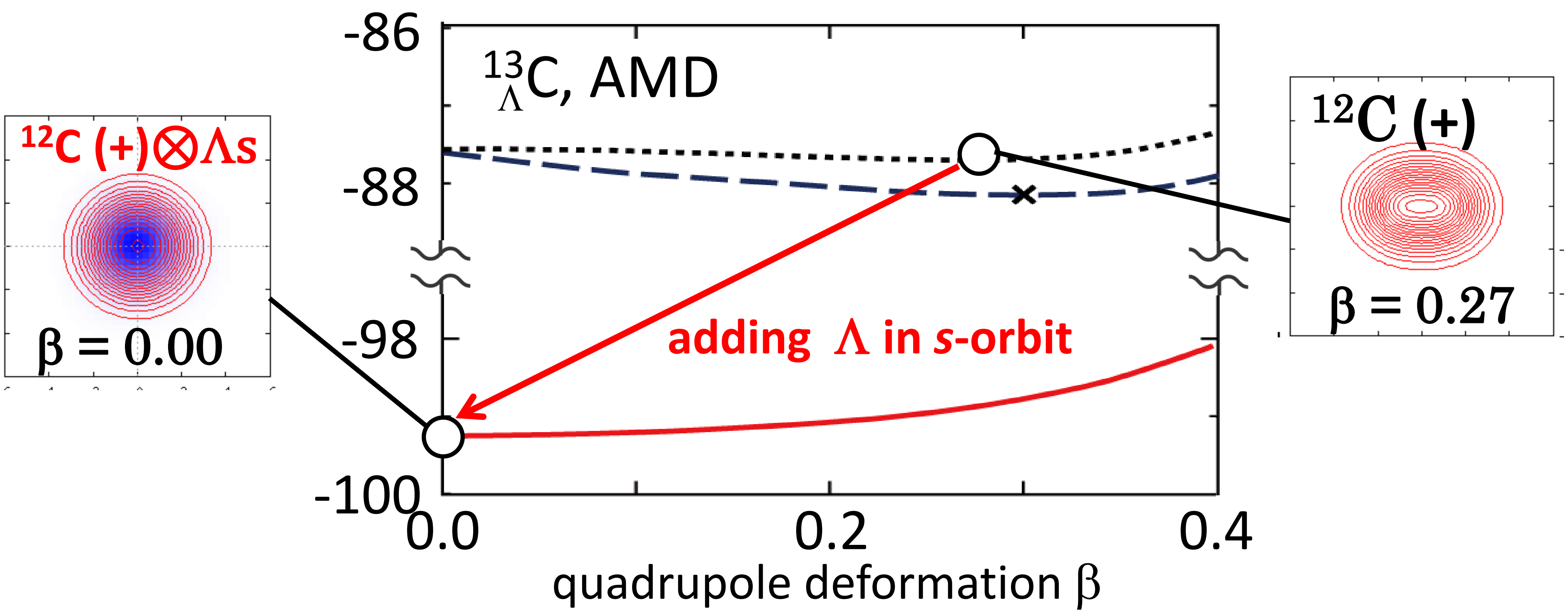
◆How to analyze from energy surface

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

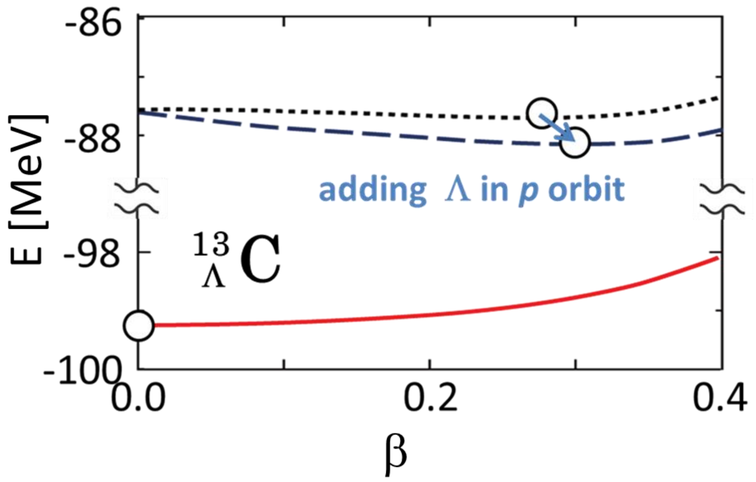


Deformation change by Λ particle

Λ in *p*-orbit enhances nuclear deformation

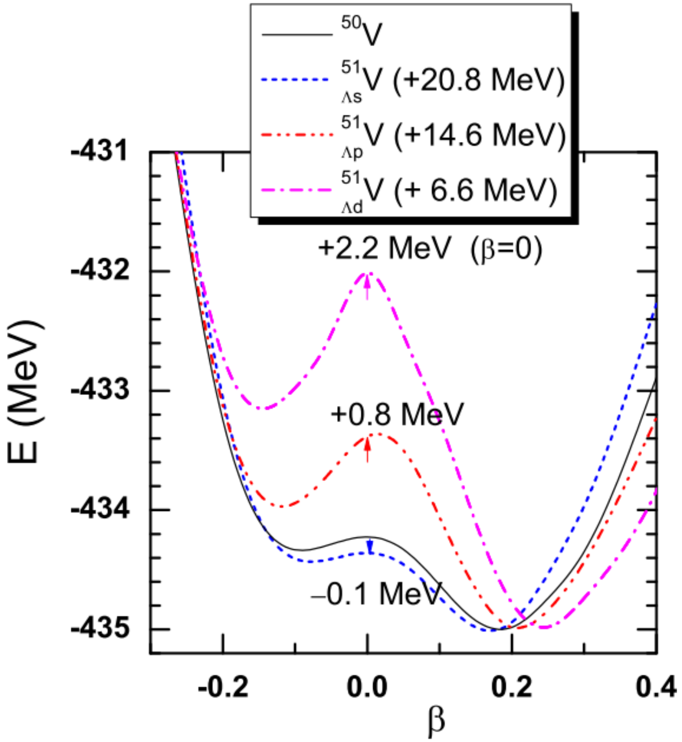
Antisymmetrized molecular dynamics (AMD)

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



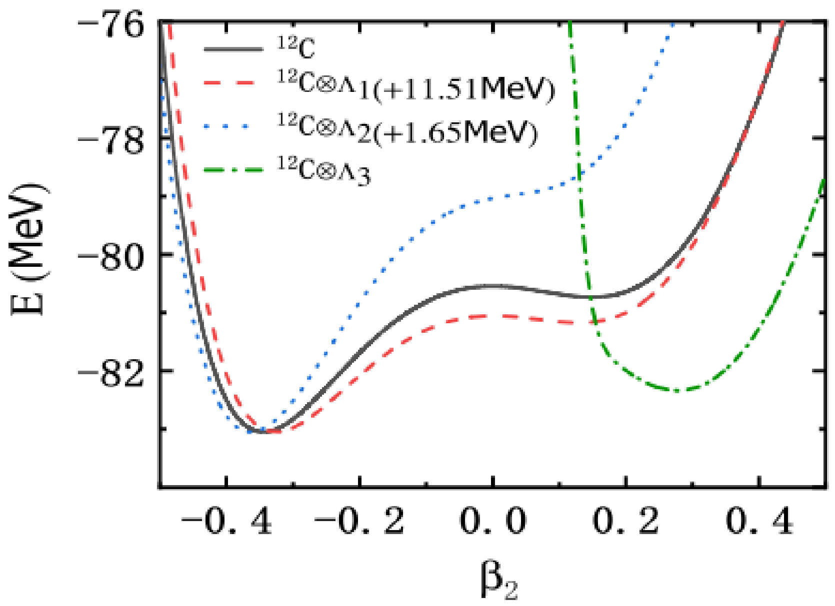
Triaxially deformed relativistic mean-field

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



Deformed Skyrme-Hartree-Fock (DSHF)

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

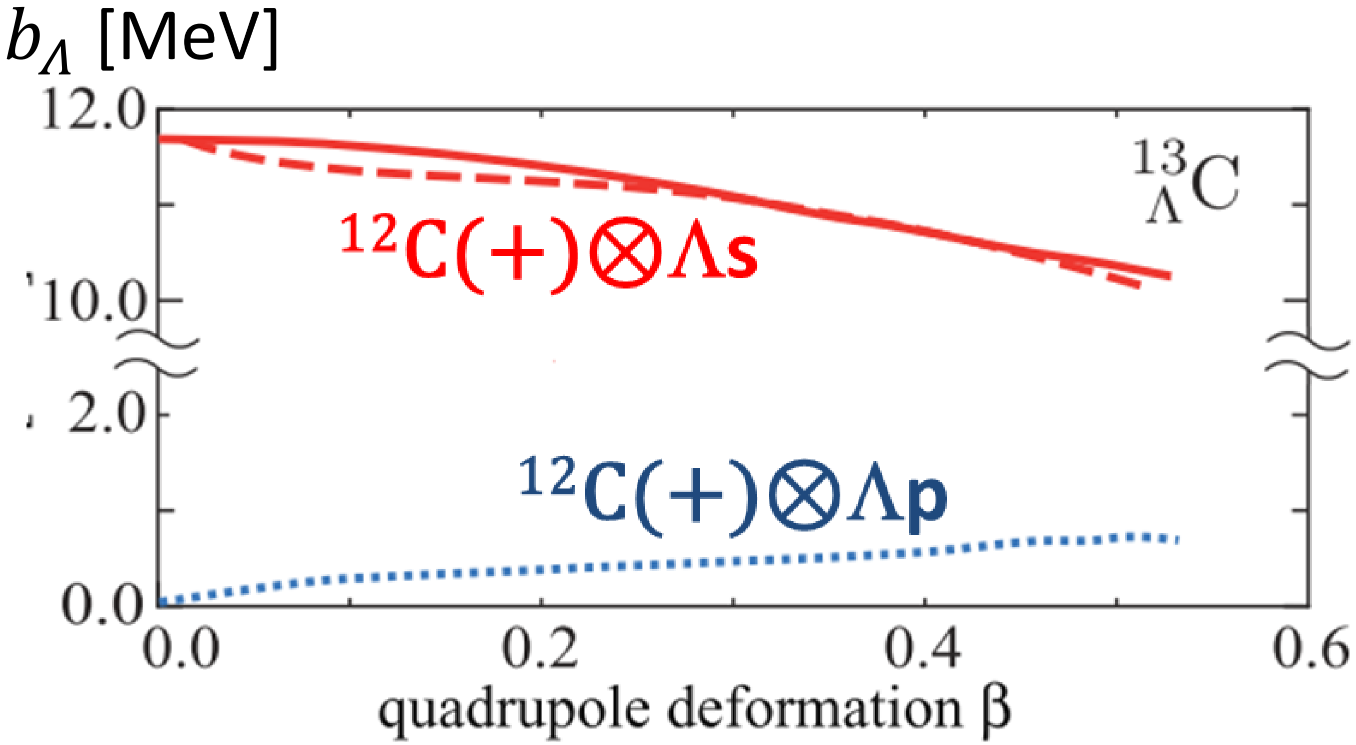


Deformation change of Λ in higher orbits such as *d*-orbit is also predicted by several papers:
W. X. Xue, et al., PRC**91**, 024327(2015), X. Y. Wu, et al., PRC**95**, 034309(2017)

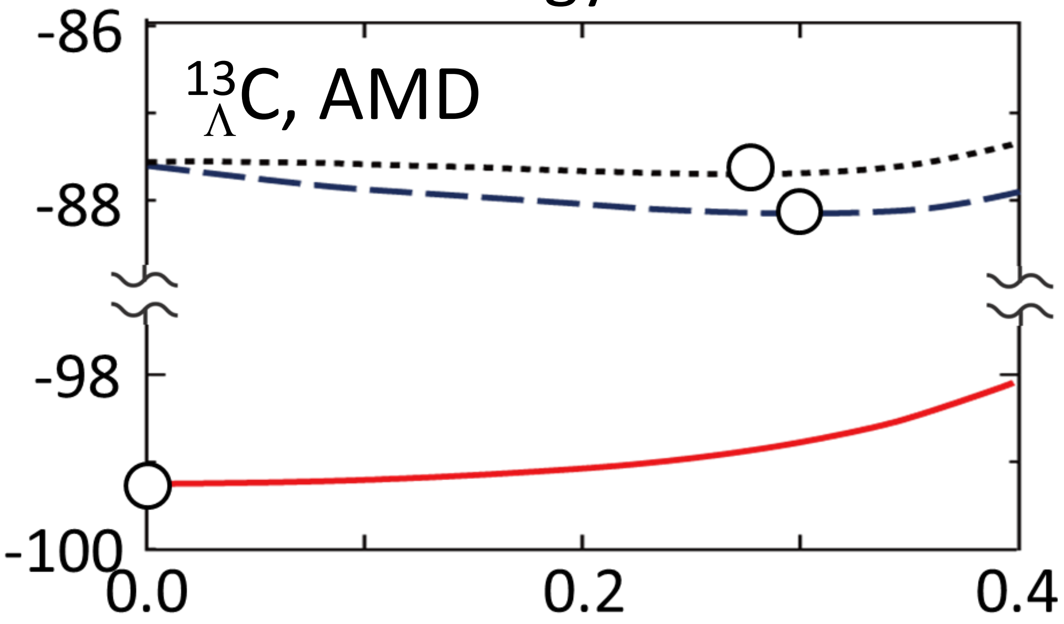
Why does Λ change nuclear deformation?

- 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

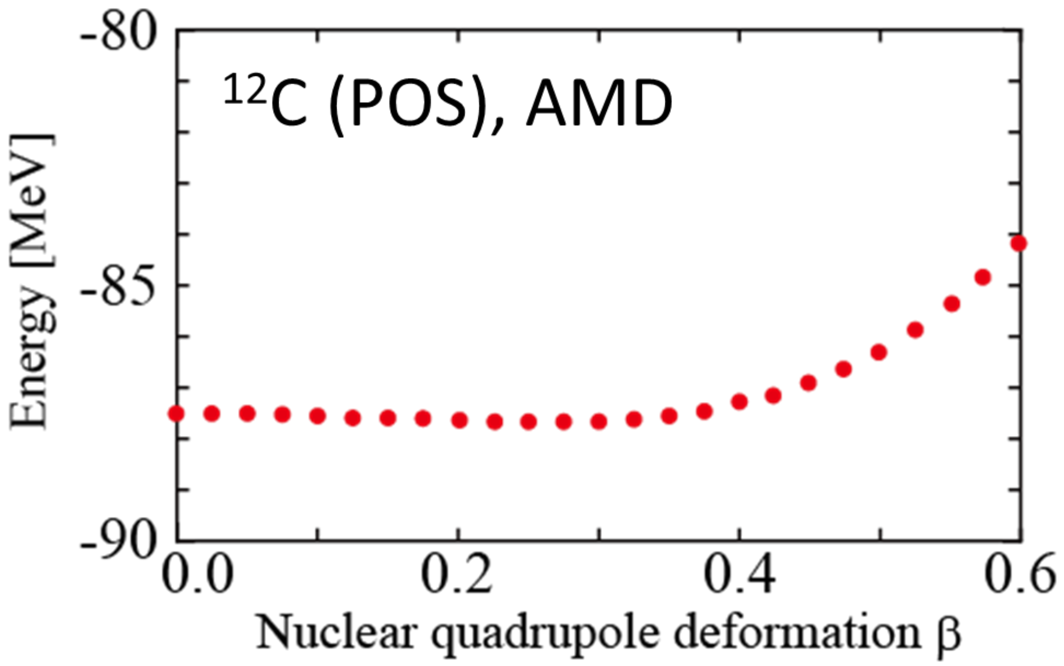


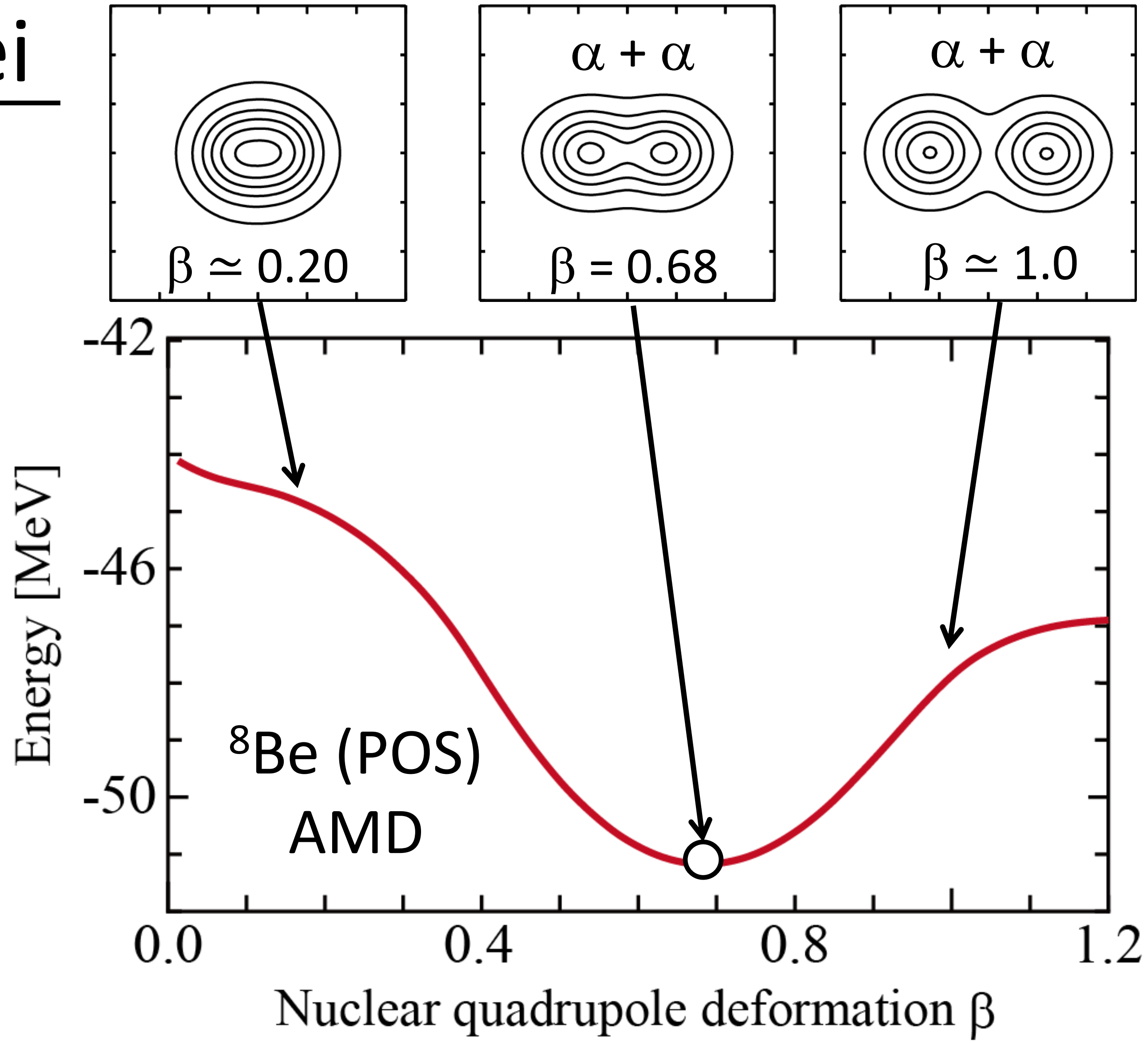
M.I, et al., PRC**83**, 044323(2011)

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

Energy surface of core nuclei

Shape of energy surface is related to nuclear structure



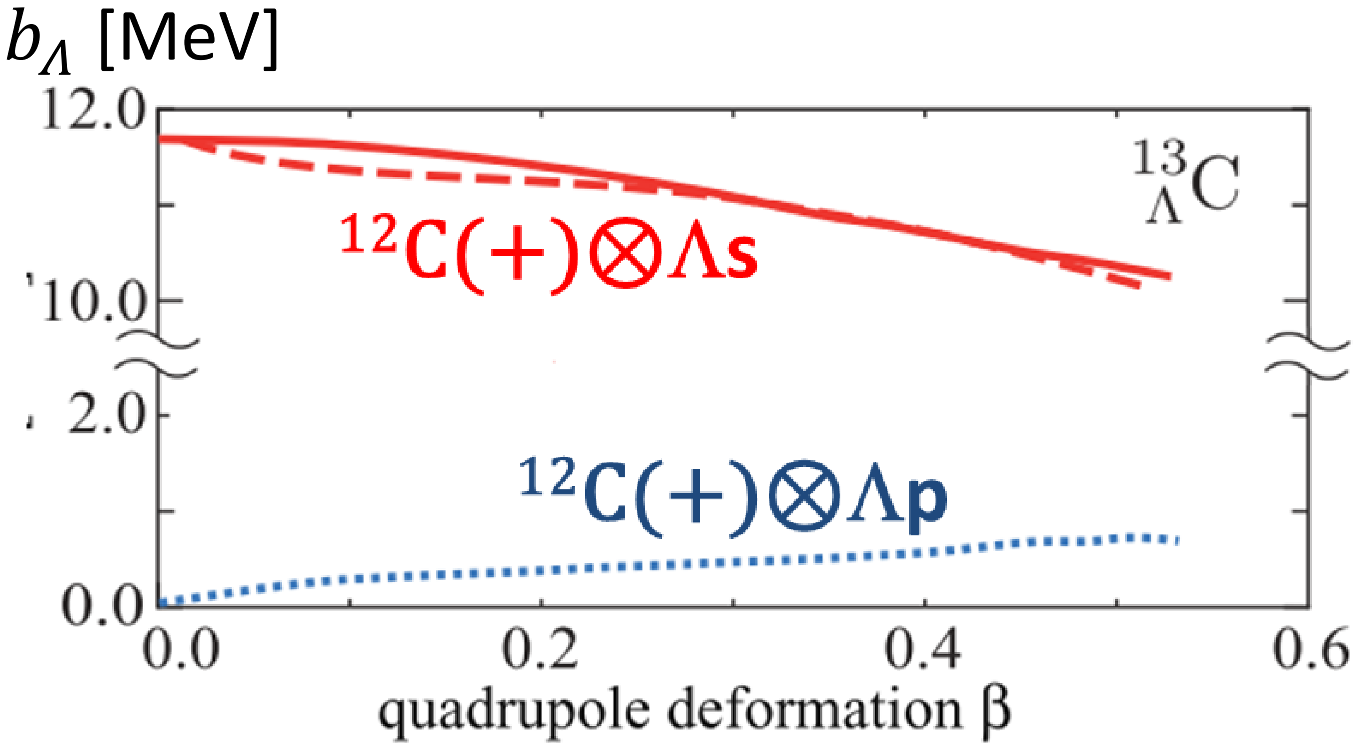


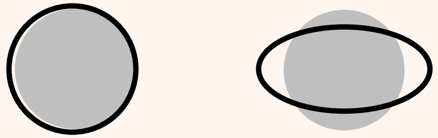
Energy increases when 2α clustering is reduced/enhanced from the minimum

Deformation change by Λ particle

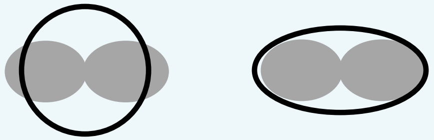
"*Overlap between Λ and N*" is the key!

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)

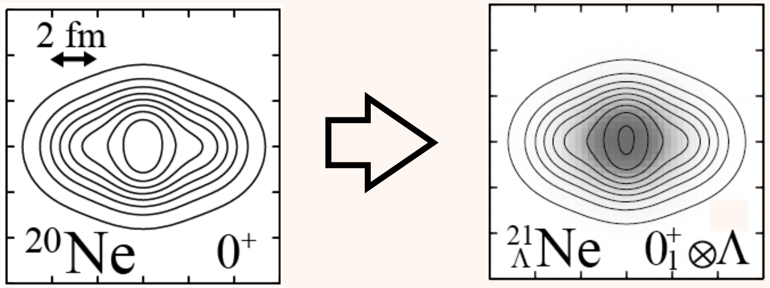
Structure dependence of "impurity effects"

◆Example: $^{21}_{\Lambda}$Ne (prediction by AMD calc)

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

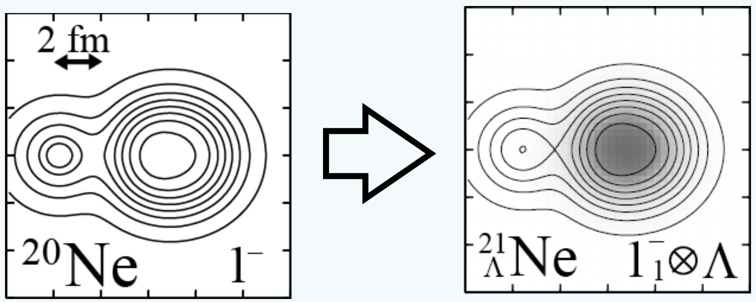
- **Shrinkage/deformation change are larger in α + ^{16}O + Λ cluster states, which appears as difference in intra-band B(E2) reduction**

Ground band



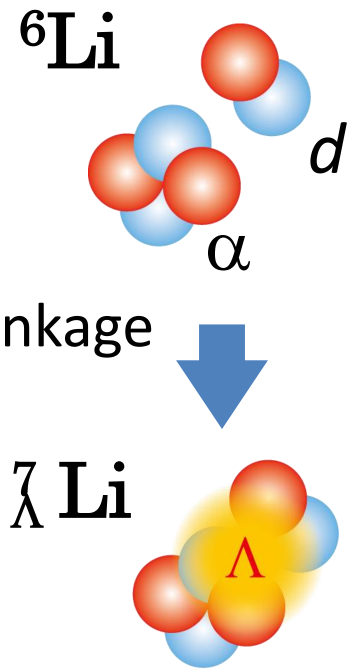
^{20}Ne $K^\pi=0^+$	r_{RMS}(fm)	$^{21}_{\Lambda}$Ne $0^+ \otimes \Lambda s$	r_{RMS}(fm)	Δr_{RMS}(fm)
0+	2.97	(1/2)+	2.92	−0.05
2+	2.96	(3/2)+	2.91	−0.05
		(5/2)+	2.91	−0.05
4+	2.93	(7/2)+	2.87	−0.06
		(9/2)+	2.88	−0.04
6+	2.87	(11/2)+	2.81	−0.05
		(13/2)+	2.83	−0.04

$K^\pi = 0^-$ (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



What will happen if a Λ particle is coupled to nuclei ?

- **Dynamical changes of nuclear structure**
  - Changes of cluster structure
  - Deformation changes

- **Sensitivity of the Λ binding energy B_Λ on nuclear structure**
  - Dependence of B_Λ on nuclear deformation
  - Mass number A dependence & many-body force effects

- **Coupling of Λ particle in *p* orbit to clustering/deformed core nuclei**
  - Genuine hypernuclear states
  - Possibility to probe nuclear deformation using Λ particle

Dependence of B_Λ on nuclear deformation

B_Λ is smaller in largely deformed state than less deformed state

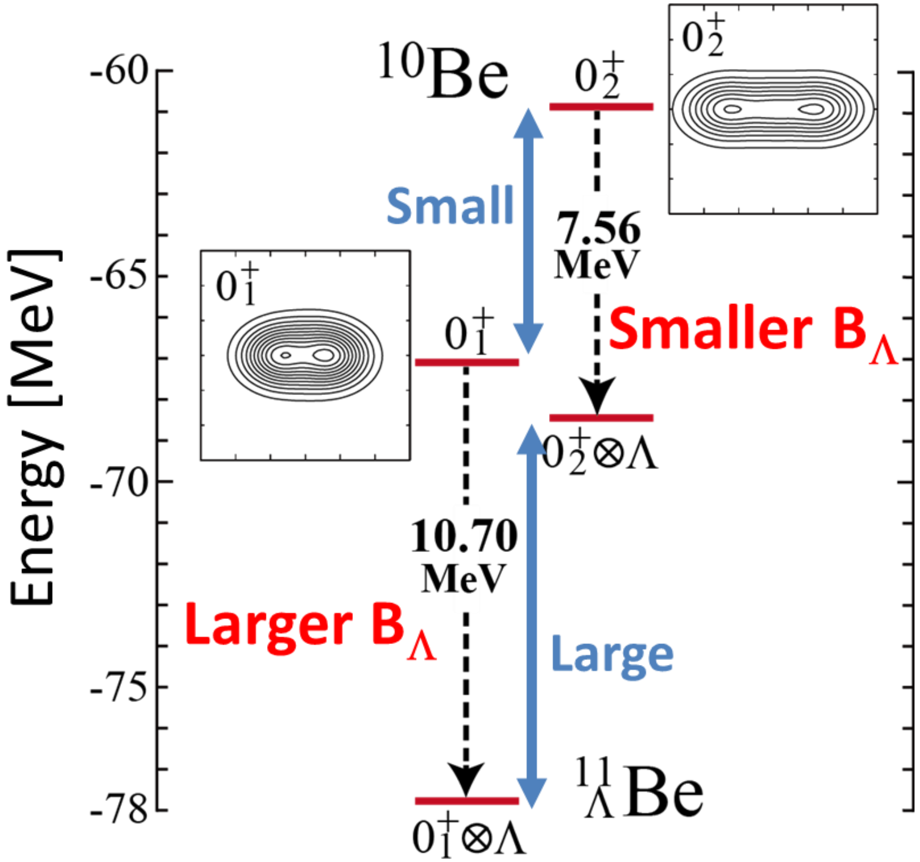
Example:

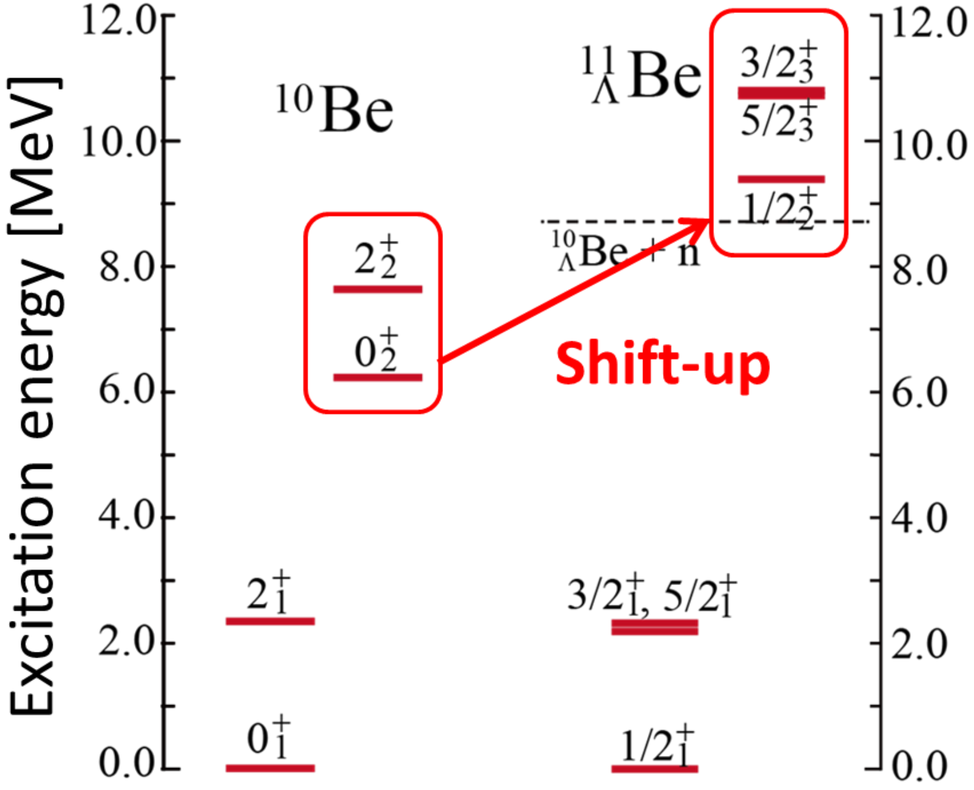
$^{11}_{\Lambda}\mathrm{Be}$

AMD calc

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

- 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





Dependence of B_Λ on nuclear structure

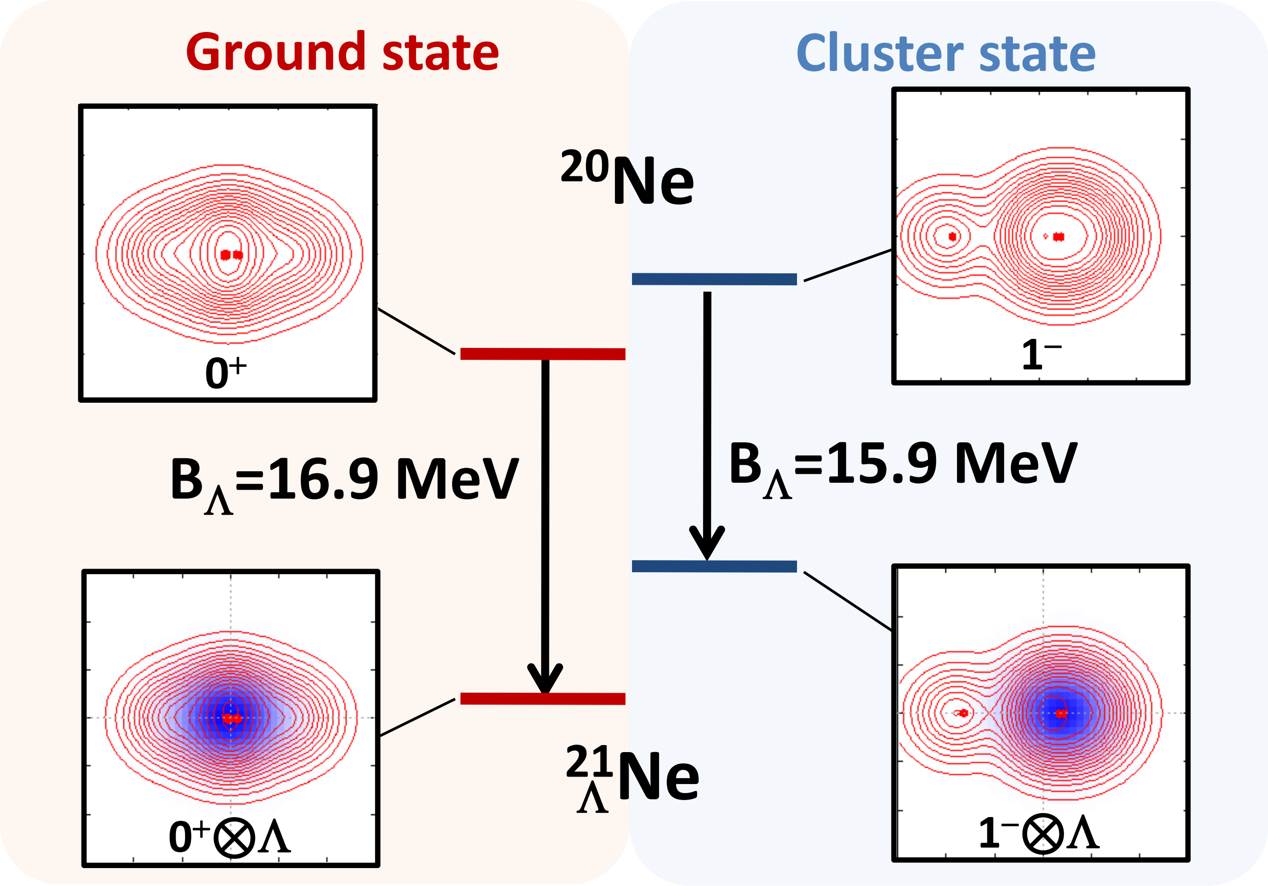
B_Λ is smaller in cluster states than mean-field like states

Example:

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

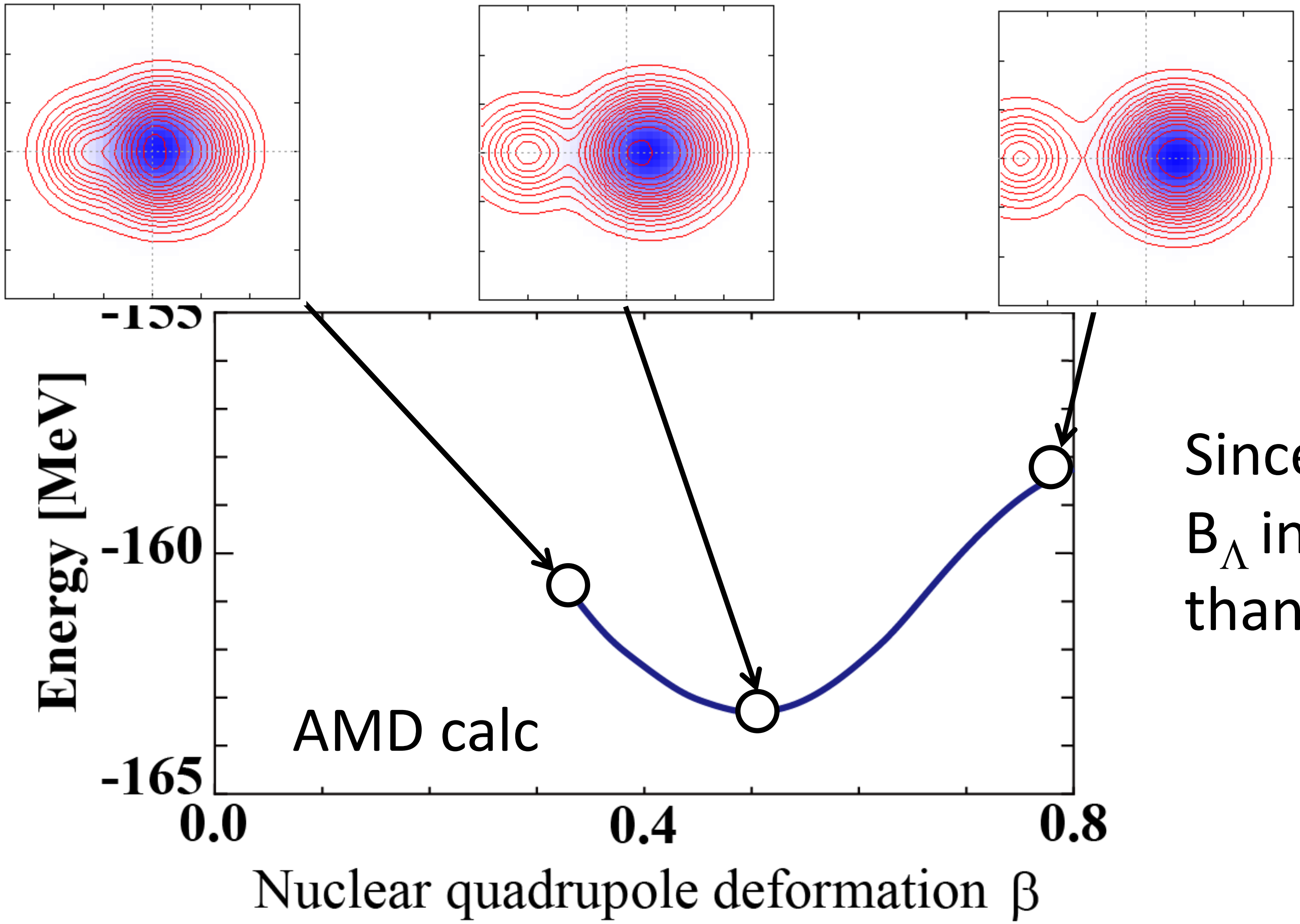
- Different structures coexist near the ground state
- Λ in s orbit changes them, but the difference remains
- Λ is localized around ^{16}O in α + ^{16}O + Λ state → difference of B_Λ

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



Dependence of B_Λ on nuclear structure

Which cluster does a Λ particle prefer in $\alpha + {}^{16}O + \Lambda$ state?



"$\alpha + {}^{17}_{\Lambda}O$ like"

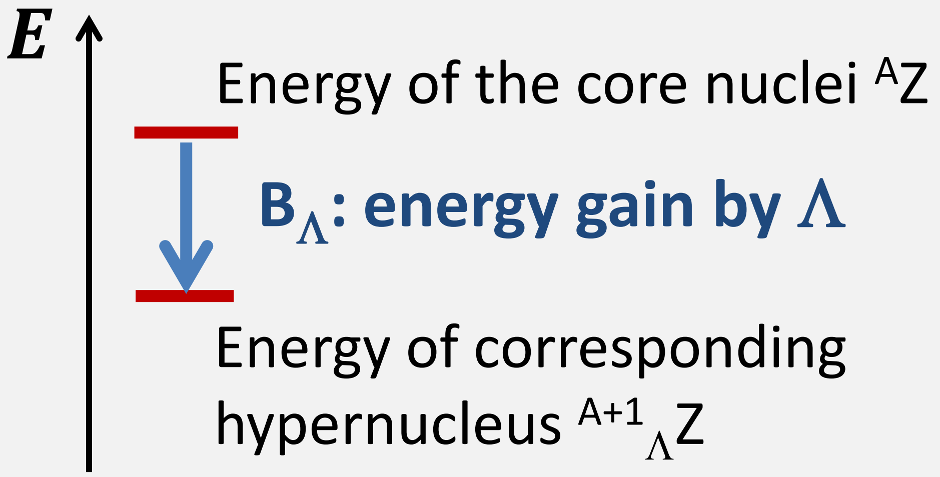
Λ prefers the ^{16}O cluster

Since $B_\Lambda({}^{21}_{\Lambda}Ne) > B_\Lambda({}^{17}_{\Lambda}O)$,
B_Λ in $\alpha + {}^{16}O + \Lambda$ states is smaller than the ground state in $^{21}_{\Lambda}Ne$

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

A-dependence of B_Λ and many-body force effects

B_Λ: a most basic quantity

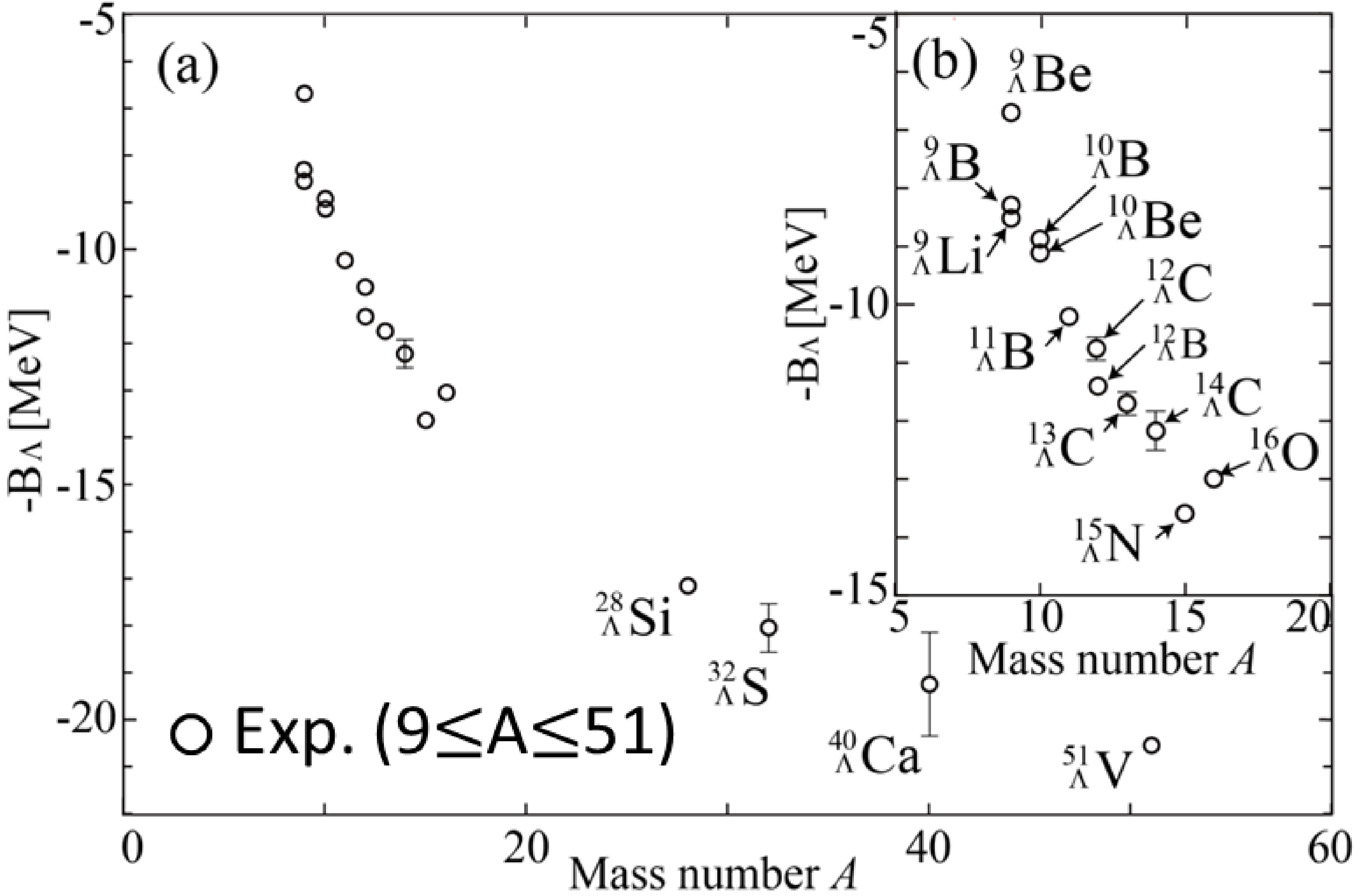


To describe A dependence of B_Λ,

- Structure of hypernuclei
- YN and YNN interactions

should be essential

Exp. data: Hashimoto & Tamura, PPNP**57**,564(2006) and references therein, Tang, *et. al.*, PRC**90**,034320(2014).



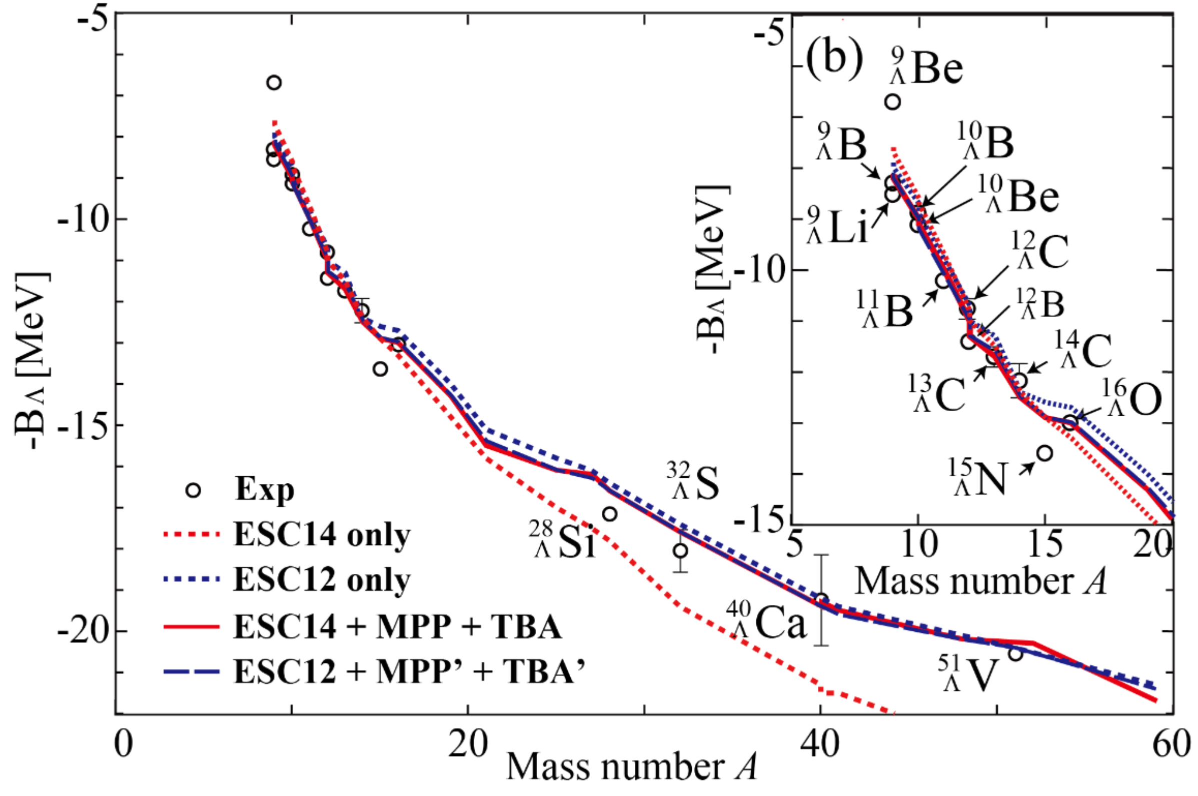
By describing structure of hypernuclei properly using appropriate ΛN interaction, many-body force (YNN) effects can be seen in A dep. of B_Λ

Some examples of theoretical attempts

Energy difference b/w B_Λ^{cal} with ΛN force and B_Λ^{exp} is a room for many-body force

AMD w/ meson exch. ΛN force (Nijmegen)

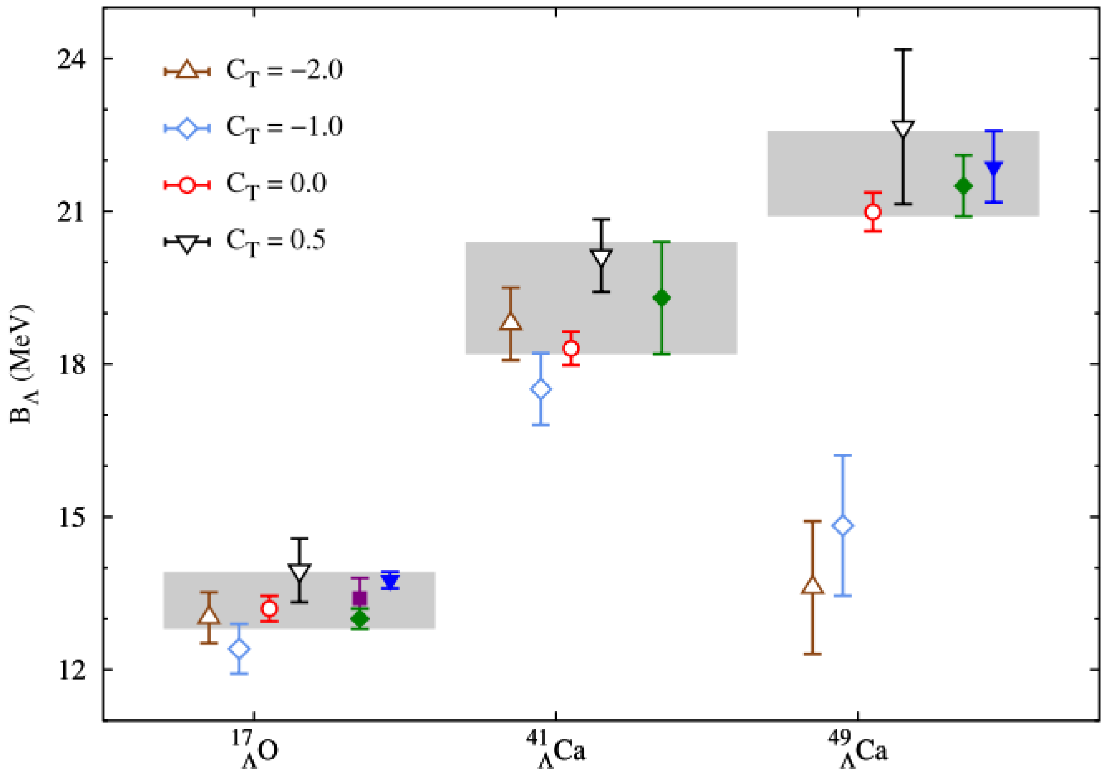
M. I, Y. Yamamoto and Th.A. Rijken, PRC**95**, 044308(2017)



- Taking into account hypernuclear deformation
- Ambiguity of ΛN potential vs. strength of ΛNN force

auxiliary field diffusion Monte Carlo (AFDMC)

D. Lonardone et al., arXiv:1711.07521v3 (2018)



- Isospin dependence of ΛNN force
- Related to future JLab exp. (E12-15-008)

Isospin-dependence of ΛNN force

◆auxiliary field diffusion Monte Carlo (AFDMC) calculation

D. Lonardone et al., arXiv:1711.07521v3 (2018)

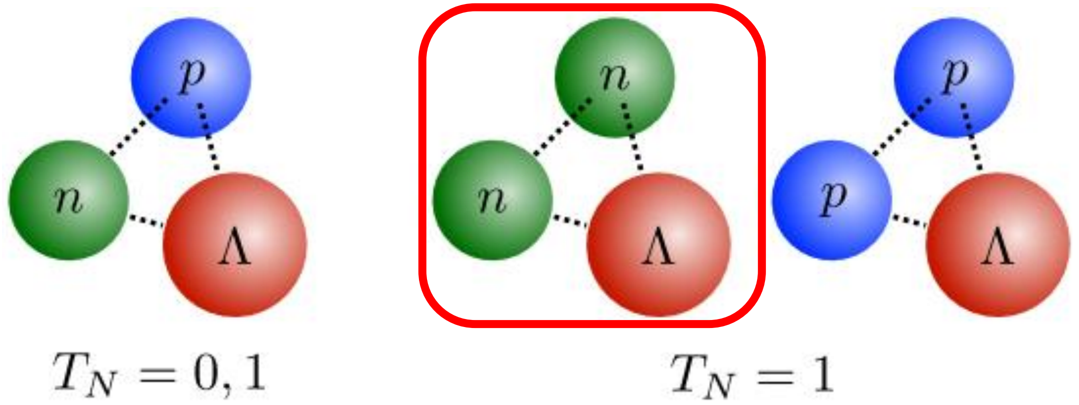
- The authors consider isospin dependence of ΛNN force related to charge symmetry breaking (CSB) in hypernuclei

- Isospin dependence is examined by artificially varying a parameter C_T

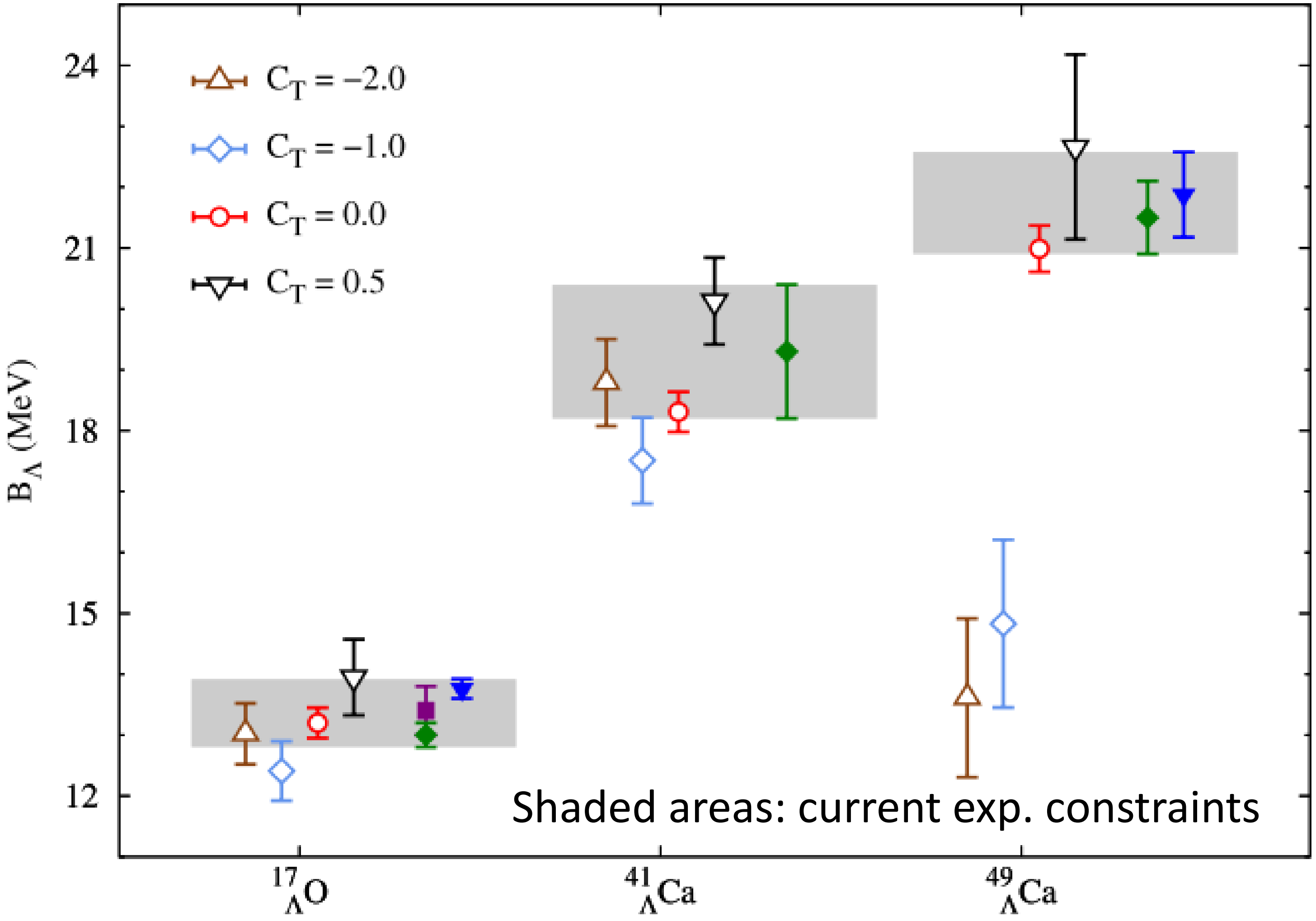
$$v^T_{\lambda ij}\,\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j = -3\,v^T_{\lambda ij}\,\mathcal{P}^{T_N=0}_{ij} + (1+C_T)\,v^T_{\lambda ij}\,\mathcal{P}^{T_N=1}_{ij}$$

$C_T = 0$: original ΛNN corr. to Λ-Σ^0 mixing mech.
$C_T = -1$: $T_N = 1$ component is off
$C_T = -2$: changing sign of $T_N = 1$ comp.

Most important in n-rich systems



Isospin-dependence of ΛNN force



D. Lonardone et al., arXiv:1711.07521v3 (2018)

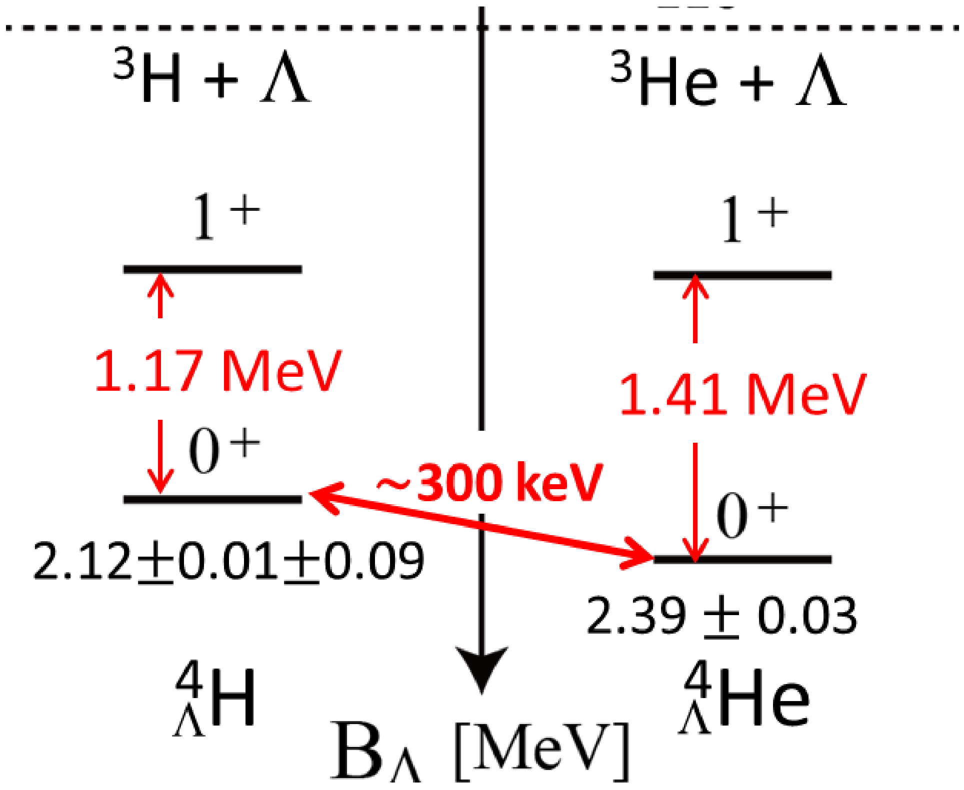
$$v^T_{\lambda ij}\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$
$$= -3\, v^T_{\lambda ij}\, \mathcal{P}^{T_N=0}_{ij} + (1 + C_T)\, v^T_{\lambda ij}\, \mathcal{P}^{T_N=1}_{ij}$$

- Isospin dep. largely affects B_Λ in heavier $Z \neq N$ hypernuclei
- Exp. data are not sufficiently accurate in $40 \lesssim A \lesssim 50$

C_T can be determined by comparing with future JLab exp. (E12-15-008), which provides us new insight on many-body force

Related topic: charge symmetry breaking (CSB)

◆CSB in A=4 Λ hypernuclei



A.Esser et al., Phys. Rev. Lett.**114**,232501(2015)
T.O. Yamamoto, et al., PRL**115**, 222501('15)

***cf.* Charge symmetry in nuclei**

- Binding energy, energy levels, … etc. are almost the same in mirror nuclei except for Coulomb effects
- Charge symmetry of nuclear force

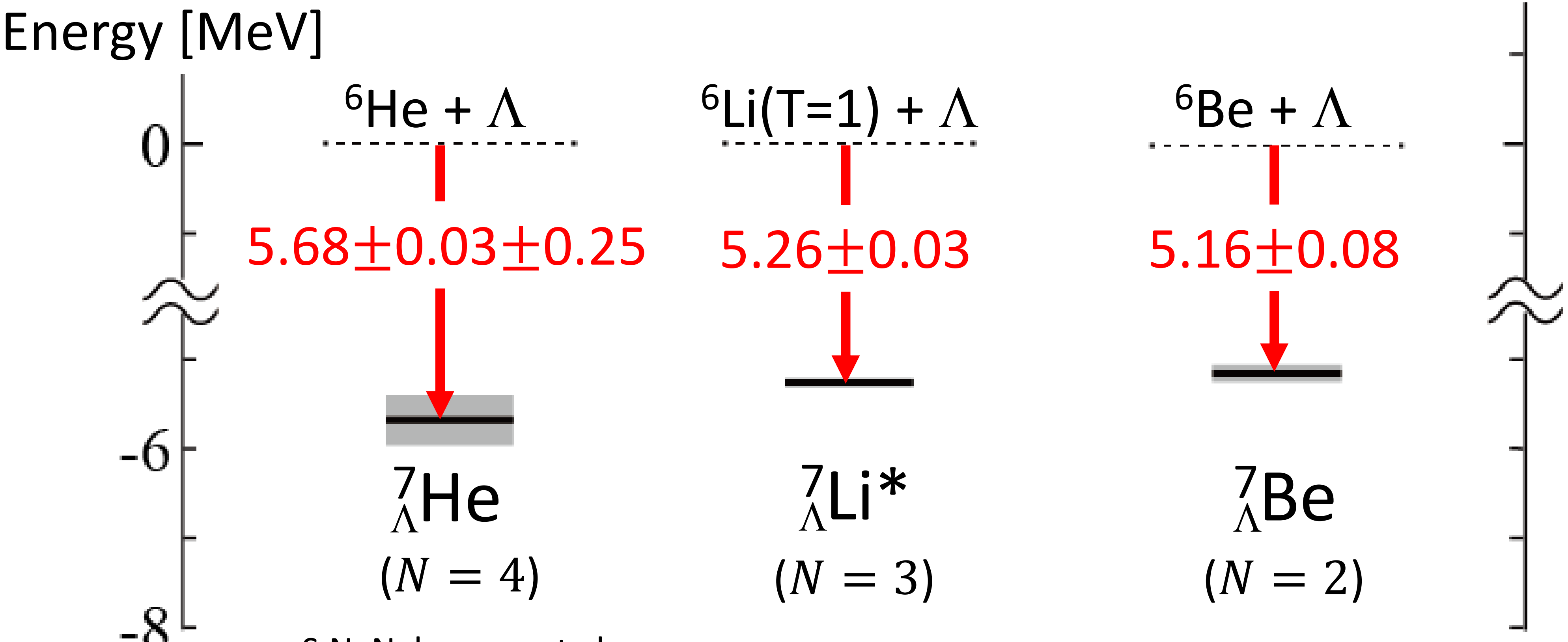
In $^4_\Lambda$H and $^4_\Lambda$He

- Large difference in B_Λ and Ex(1^+)
- Λp and Λn interactions are different?
- Many-body effects with hyperon mixing?

Related topic: charge symmetry breaking (CSB)

◆CSB in A=7 hypernuclear isotriplet (T=1)

- **Different trend from A=4 Λ hypernuclei: larger B_Λ as N increases**



S.N. Nakamura et al., PRL**110**(2013) 012502

JLab E01-011

H. Tamura et al., PRL**84**,(2000)5963

M.Juric et al., NPB**52**(1973)1

What will happen if a Λ particle is coupled to nuclei ?

- **Dynamical changes of nuclear structure**
  - Changes of cluster structure
  - Deformation changes

- **Sensitivity of the Λ binding energy B_Λ on nuclear structure**
  - Dependence of B_Λ on nuclear deformation
  - Mass number A dependence & many-body force effects

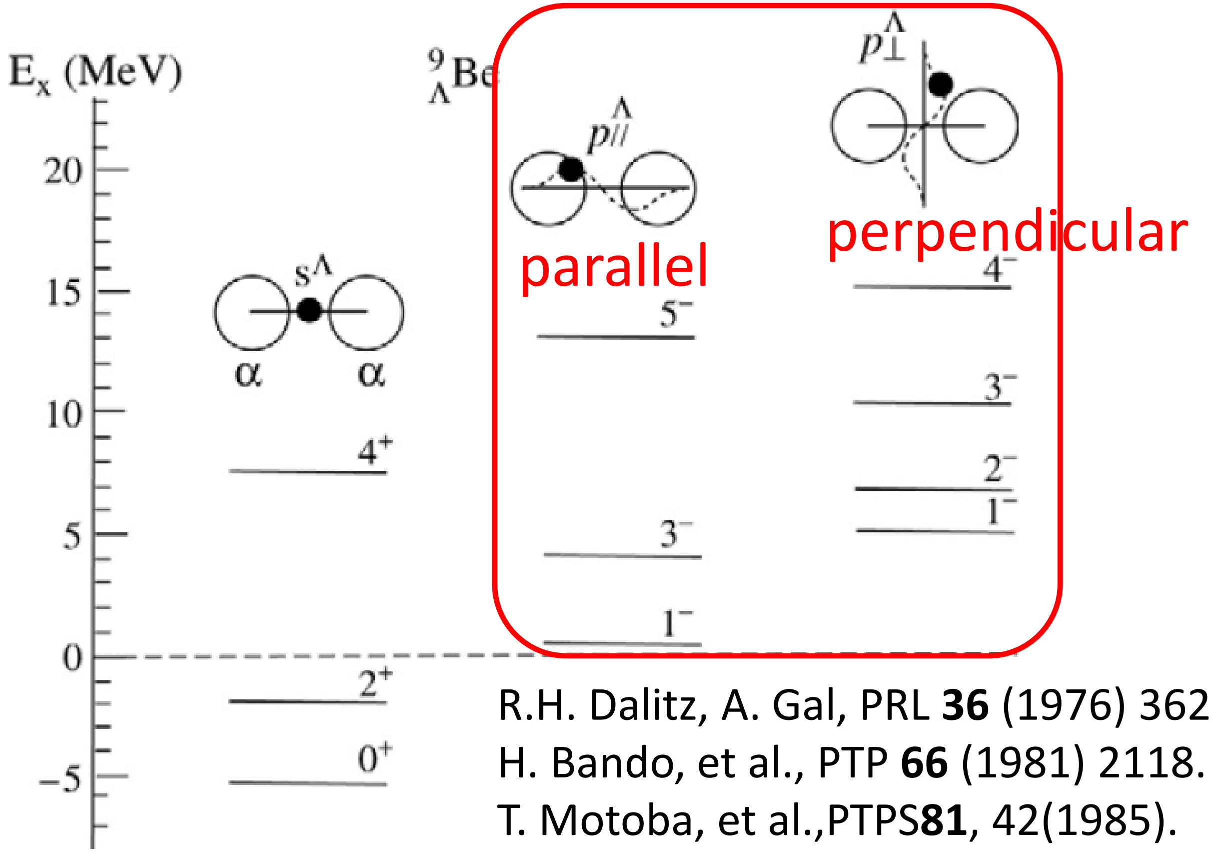
- **Coupling of Λ particle in *p* orbit to clustering/deformed core nuclei**
  - Genuine hypernuclear states
  - Possibility to probe nuclear deformation using Λ particle

Genuine hypernuclear states in $^{9}_{\Lambda}$Be

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

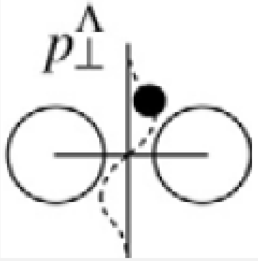
Two rotational bands as *p*-states
- Anisotropic *p* orbit of Λ hyperon
- Axial symmetry of 2α clustering

→ *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).

p states in $^{9}_{\Lambda}$Be



$\fallingdotseq$ ^{9}Be

"^{9}Be analog states"

Forbidden for n in ^{9}Be due to Pauli principle

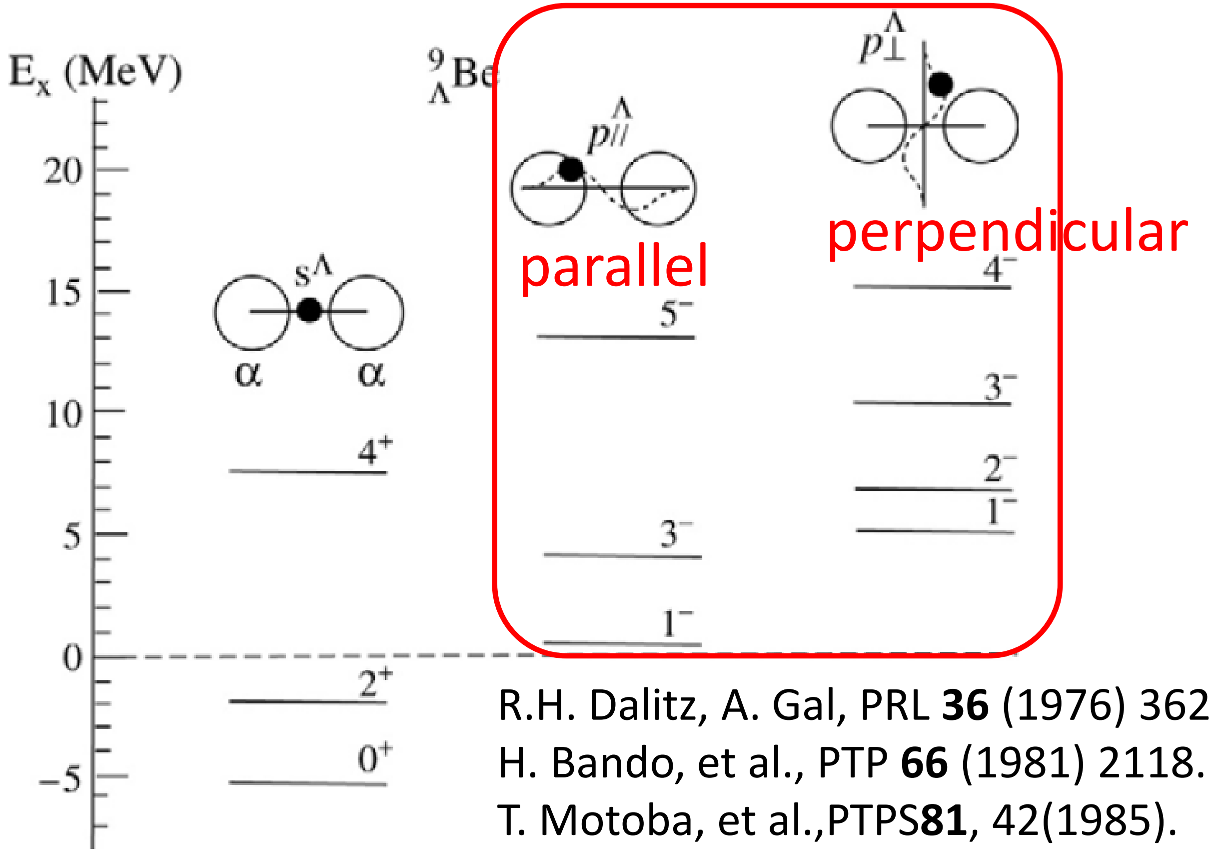
"genuine hypernuclear states"

Genuine hypernuclear states in $^{9}_{\Lambda}$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.
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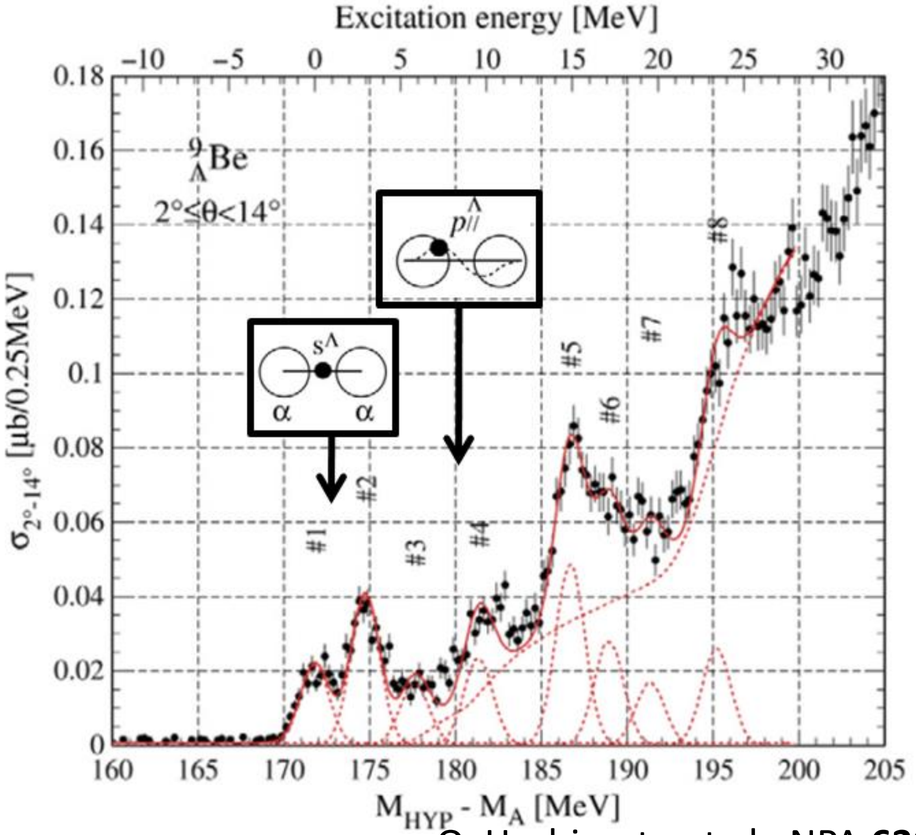
T. Motoba, et al.,PTPS**81**, 42(1985).



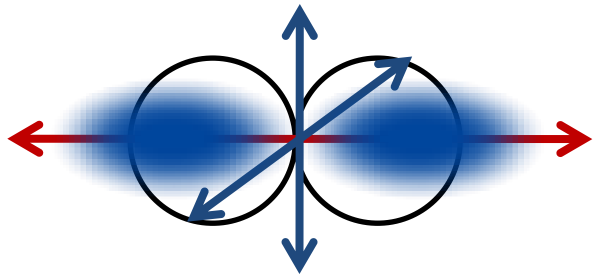
O. Hashimoto et al., NPA **639** (1998) 93c.

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

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

Genuine hypernuclear states:

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

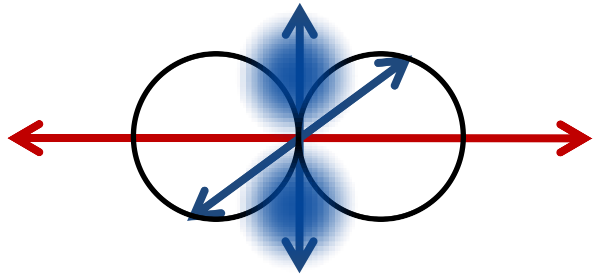


Large overlap

Deeply bound

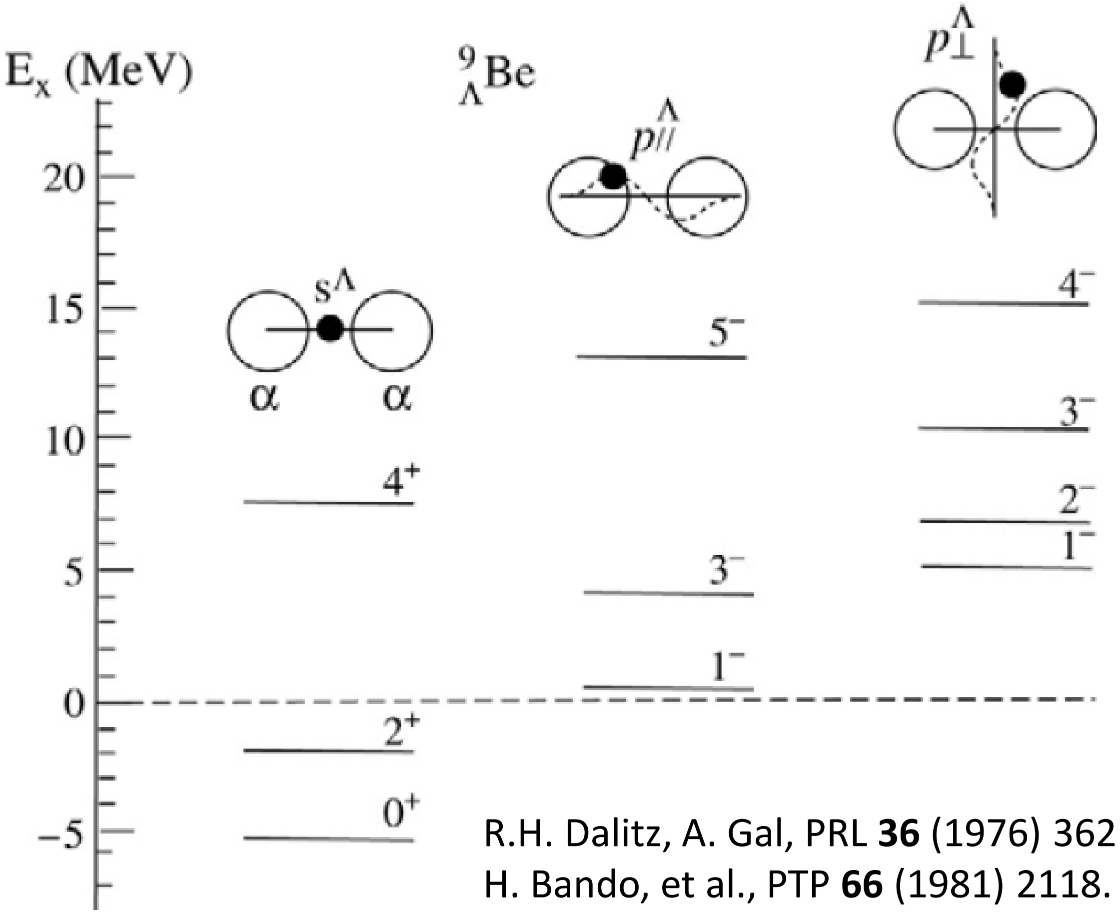
^{9}Be analog states:

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



Small overlap

Shallowly bound



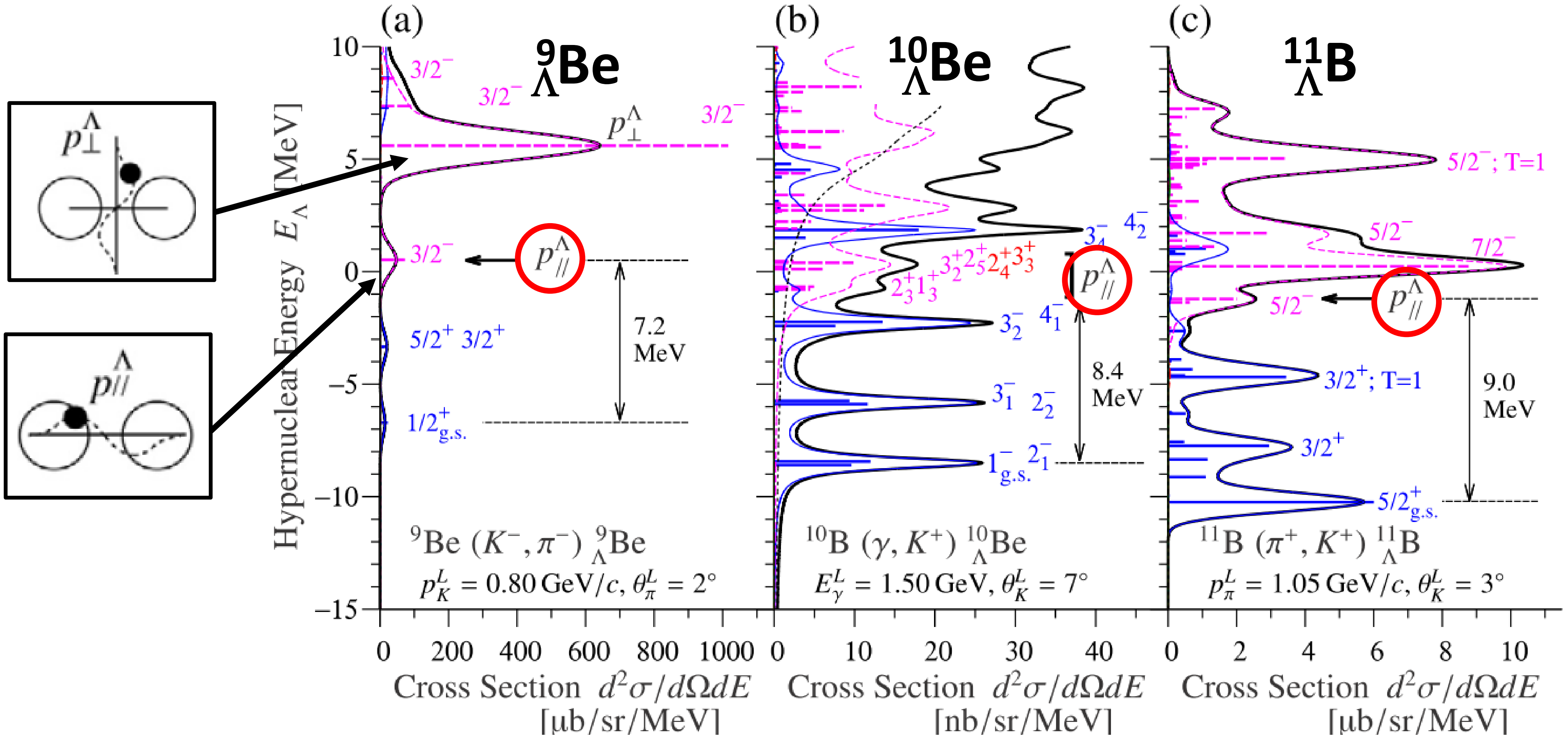
R.H. Dalitz, A. Gal, PRL **36** (1976) 362.
H. Bando, et al., PTP **66** (1981) 2118.
T. Motoba, et al.,PTPS**81**, 42(1985).

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

Genuine hypernuclear states in the other hypernuclei

Genuine hypernuclear states are predicted not only in $^{9}_{\Lambda}$Be but $^{10}_{\Lambda}$Be & $^{11}_{\Lambda}$Be

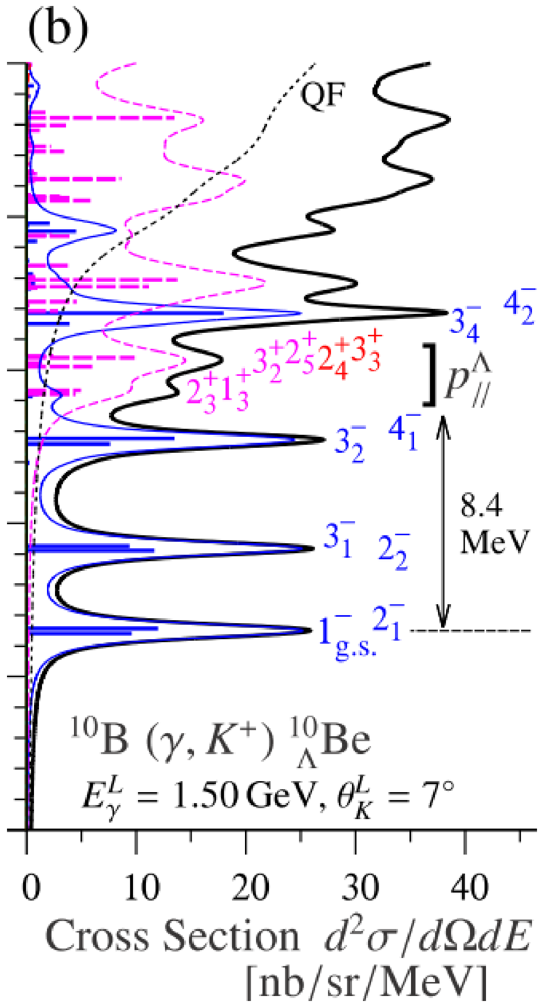
Shell model + DWIA calc. by Umeya et al., EPJ Web of Conferernce **271**, 01010(2022)



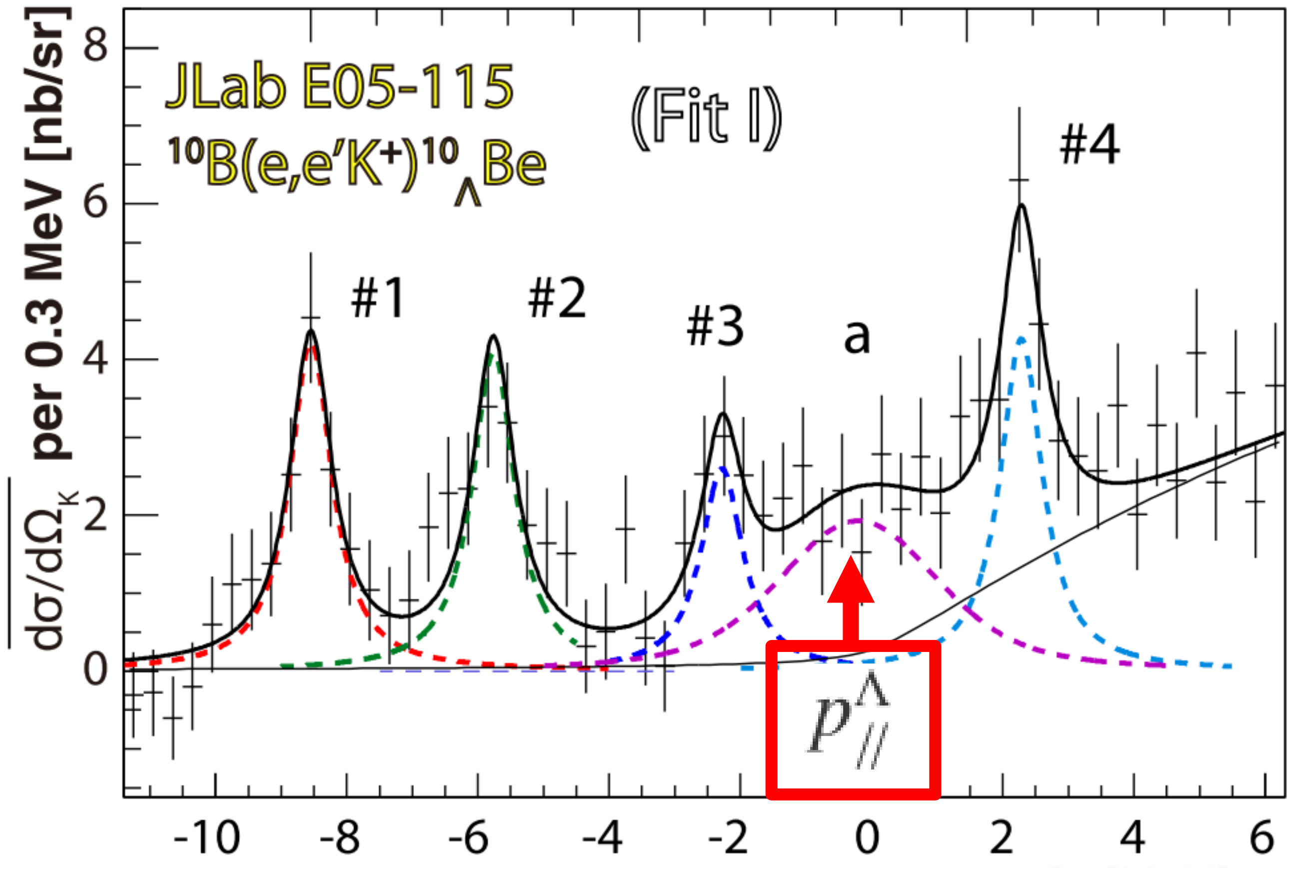
Genuine hypernuclear states in the other hypernuclei

$^{10}_{\Lambda}\text{Be}$

Shell model + DWIA by Umeya



T. Gogami et al., PRC**93**, 034314(2016)



Bump structure "a" can be interpreted as genuine hypernuclear states

Coupling of Λ in *p* orbit to symmetric cluster structure causes splitting of *p* states

Coupling of Λ in *p* orbit to triaxially deformed nuclei

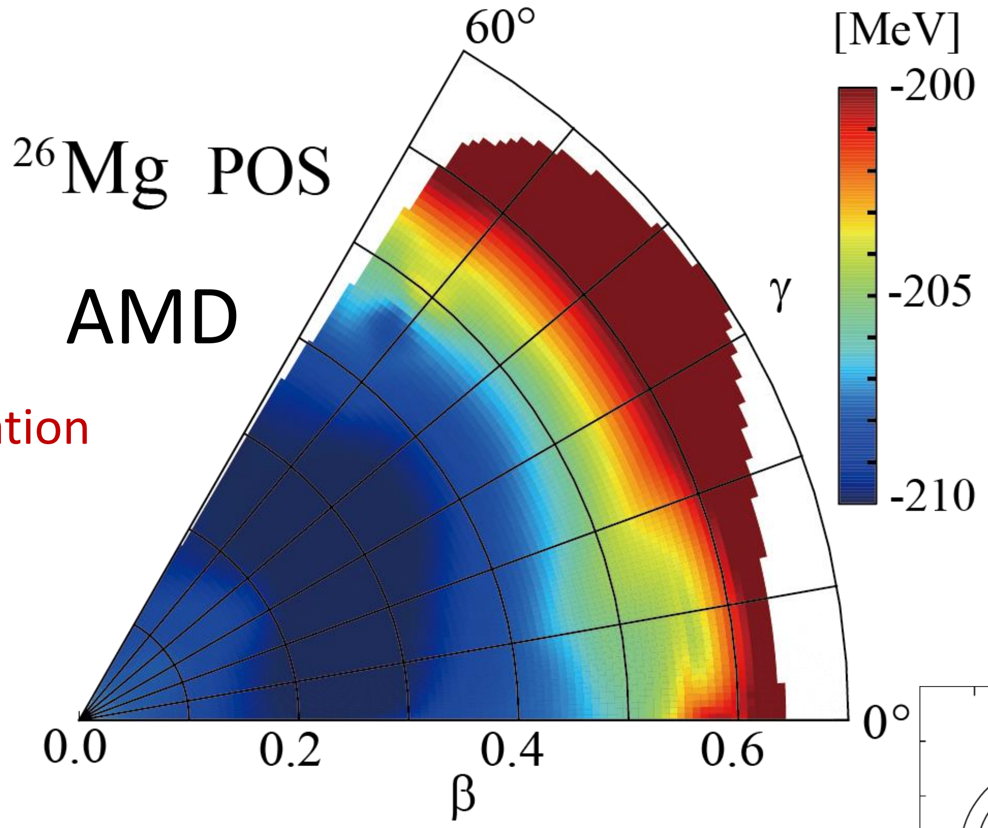
^{26}Mg

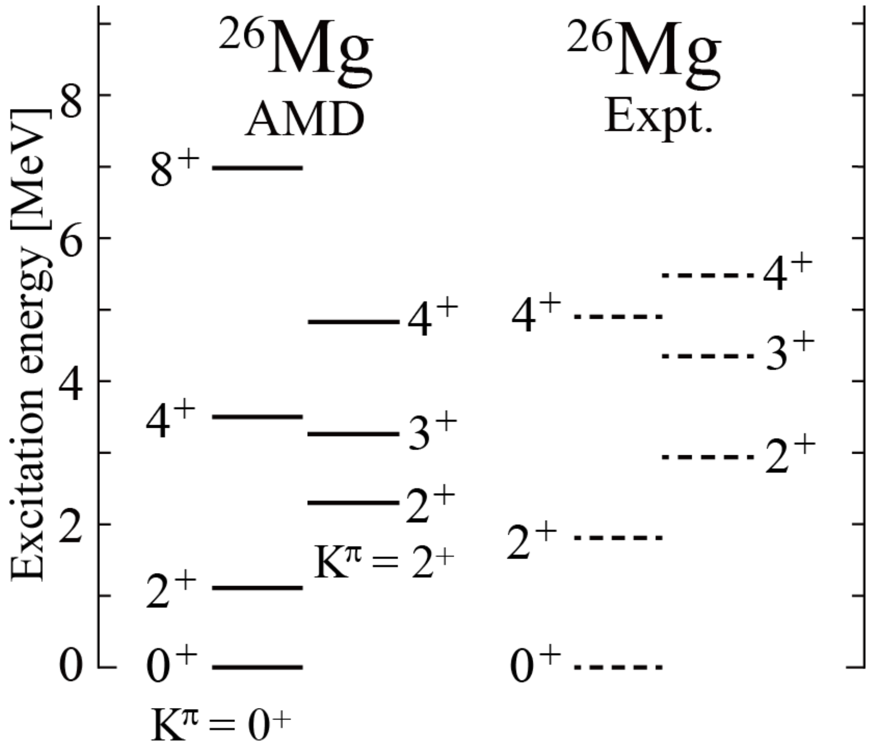
- Shell gap in Nilsson diagram: Z=12 (prolate) vs. N=14 (oblate) → triaxial
- β,γ-softness is discussed by several authors

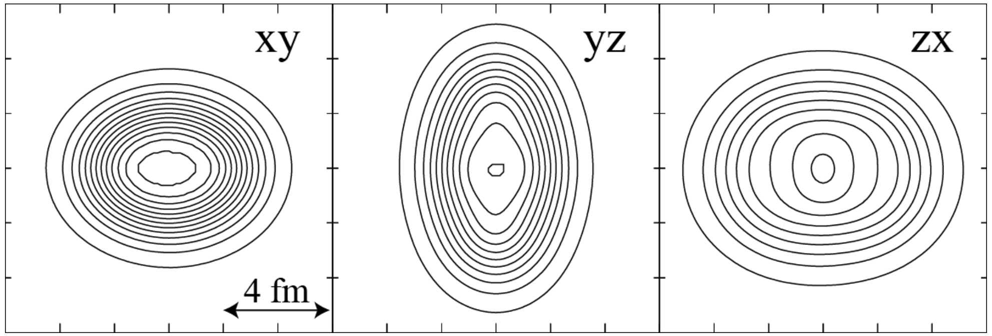
Terasaki et al. NPA**621**(1997)
Rodrıguez-Guzman et al. NPA**709** (2002)
Peru et al PRC**77** (2008)
Hinohara, Kanada-En'yo PRC**83** (2011)

AMD

β: degree of deformation
γ: (tri)axiality

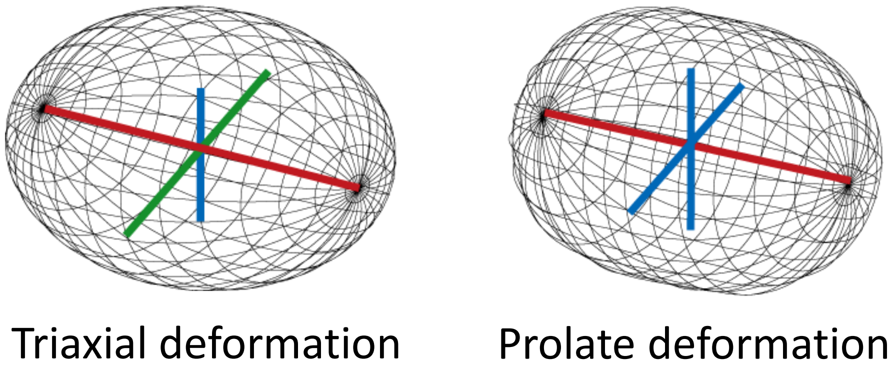




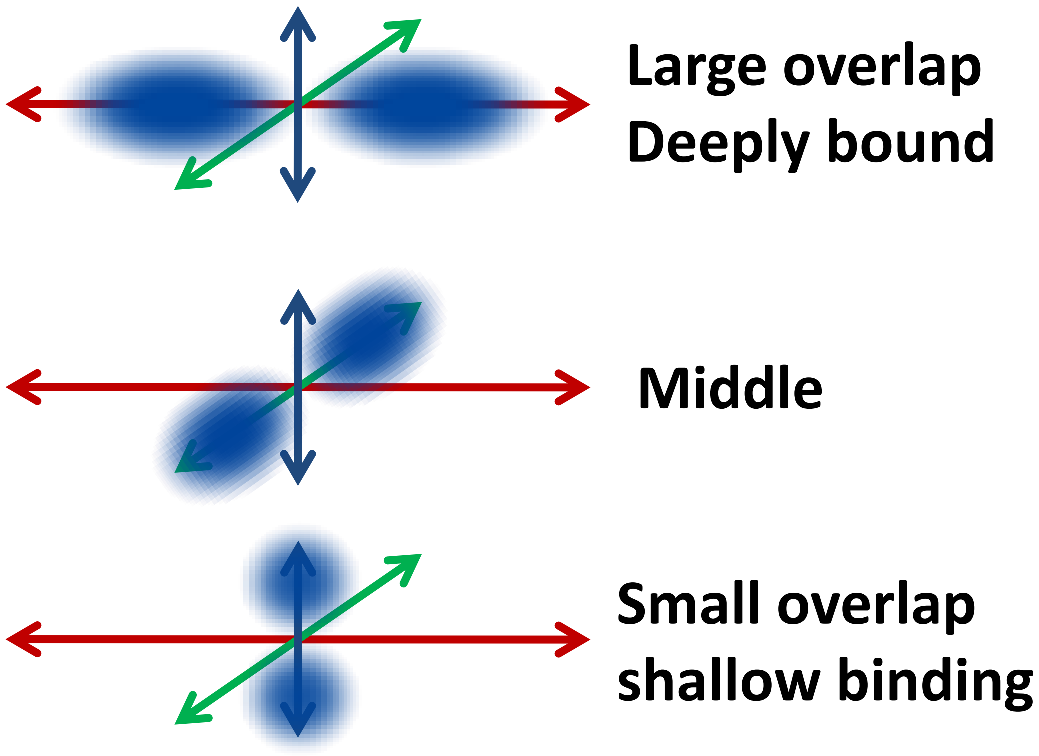


What will happen if Λ in p orbit is coupled to triaxially deformed ^{26}Mg ?

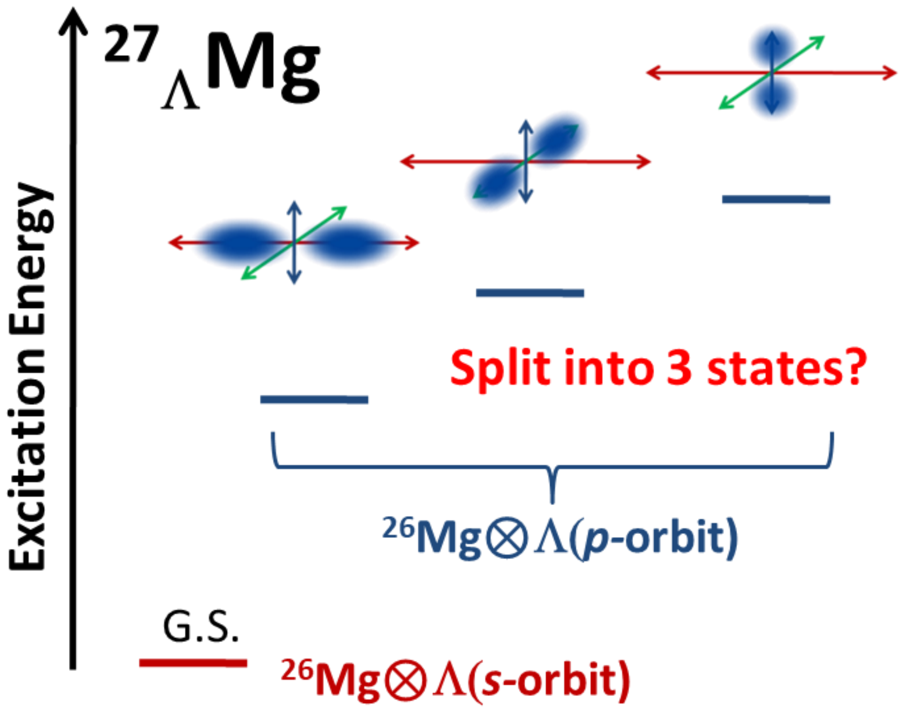
Triaxial deformation



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



Candidate: Mg hypernuclei

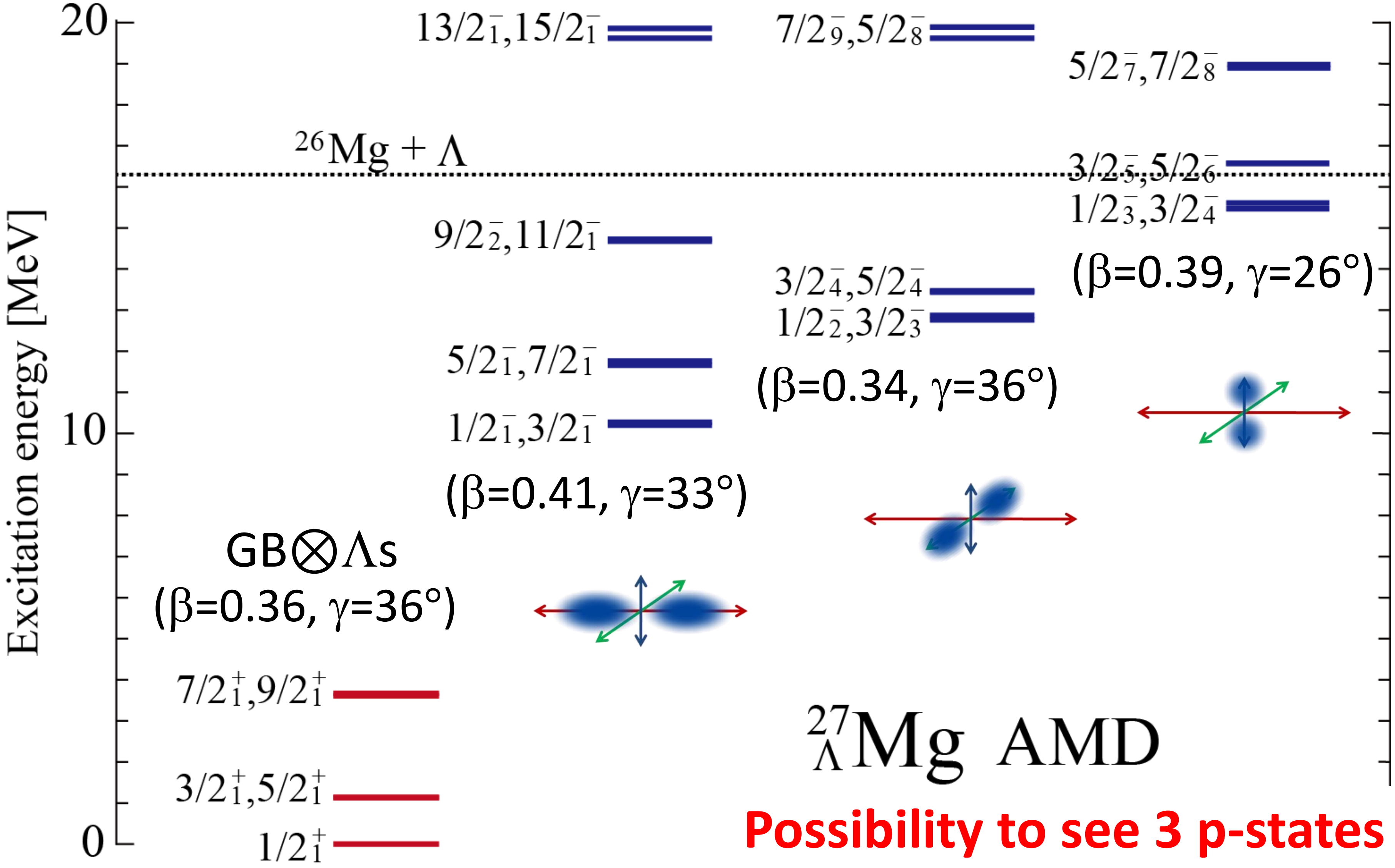


Observing the 3 different *p*-states is strong evidence of triaxial deformation

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

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

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



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

Possibility to see 3 p-states by ^{27}Al(e,e'K+)$^{27}{}_{\Lambda}$Mg

Summary

In Λ hypernuclei, by the coupling of Λ, we can expect following phenomena:

Dynamical changes of nuclear structure

- Changes of cluster structure
- Deformation changes

→ **Structure changes depending on core structure**

Sensitivity of B_Λ on nuclear structure

- B_Λ depending on nuclear deformation
- Both hyperonic interactions and structure of hypernuclei are important in A-dep. of B_Λ

→ **Many-body effects in Λ hypernuclei** future exp. at JLab (E12-15-008)

Coupling of Λ particle to clustering/deformed core nuclei

- Genuine hypernuclear states not only in $^{9}_{\Lambda}$Be but also $^{10}_{\Lambda}$Be JLab E05-115
- Possibility to probe nuclear triaxial deformation using Λ in $^{27}_{\Lambda}$Mg