Collective excitations of Λ hypernuclei

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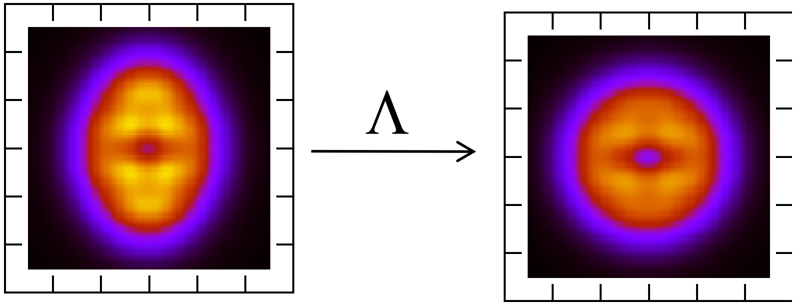


1. *Introduction*
2. *Deformation of Lambda hypernuclei*
3. *Collective rotational excitations of hypernuclei*
4. *Vibrational excitations of spherical hypernuclei*
5. *Summary*

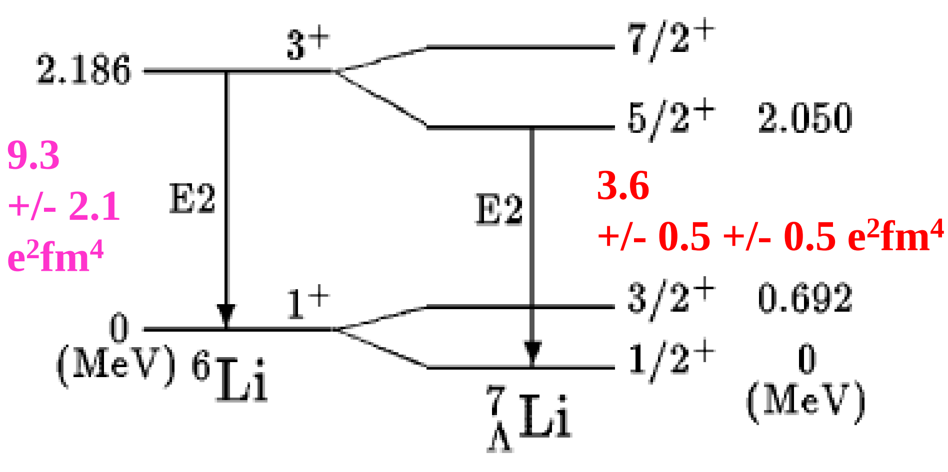
Introduction

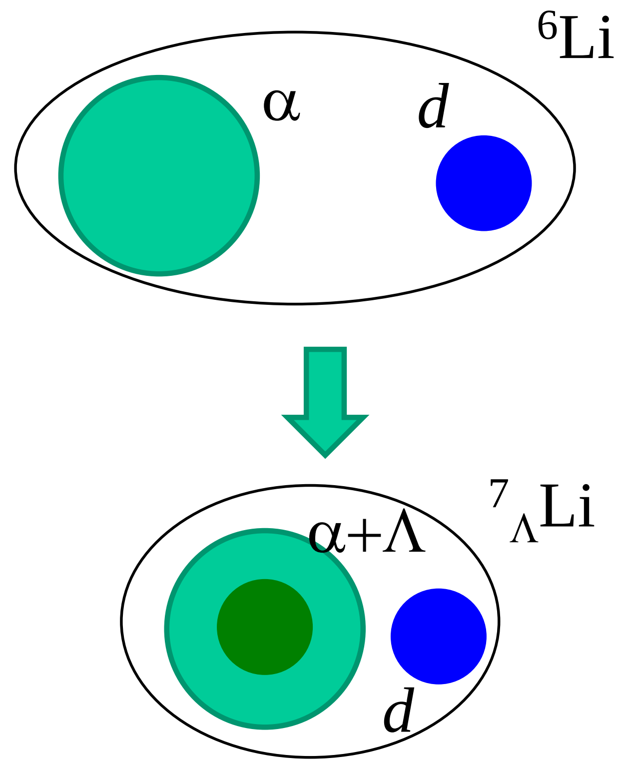
Impurity effects: one of the main interests of hypernuclear physics

how does Λ affect several properties of atomic nuclei?

- size, shape, density distribution, single-particle energy, shell structure, fission barrier……

the most prominent example:
the reduction of B(E2) in $^{7}_{\Lambda}$Li



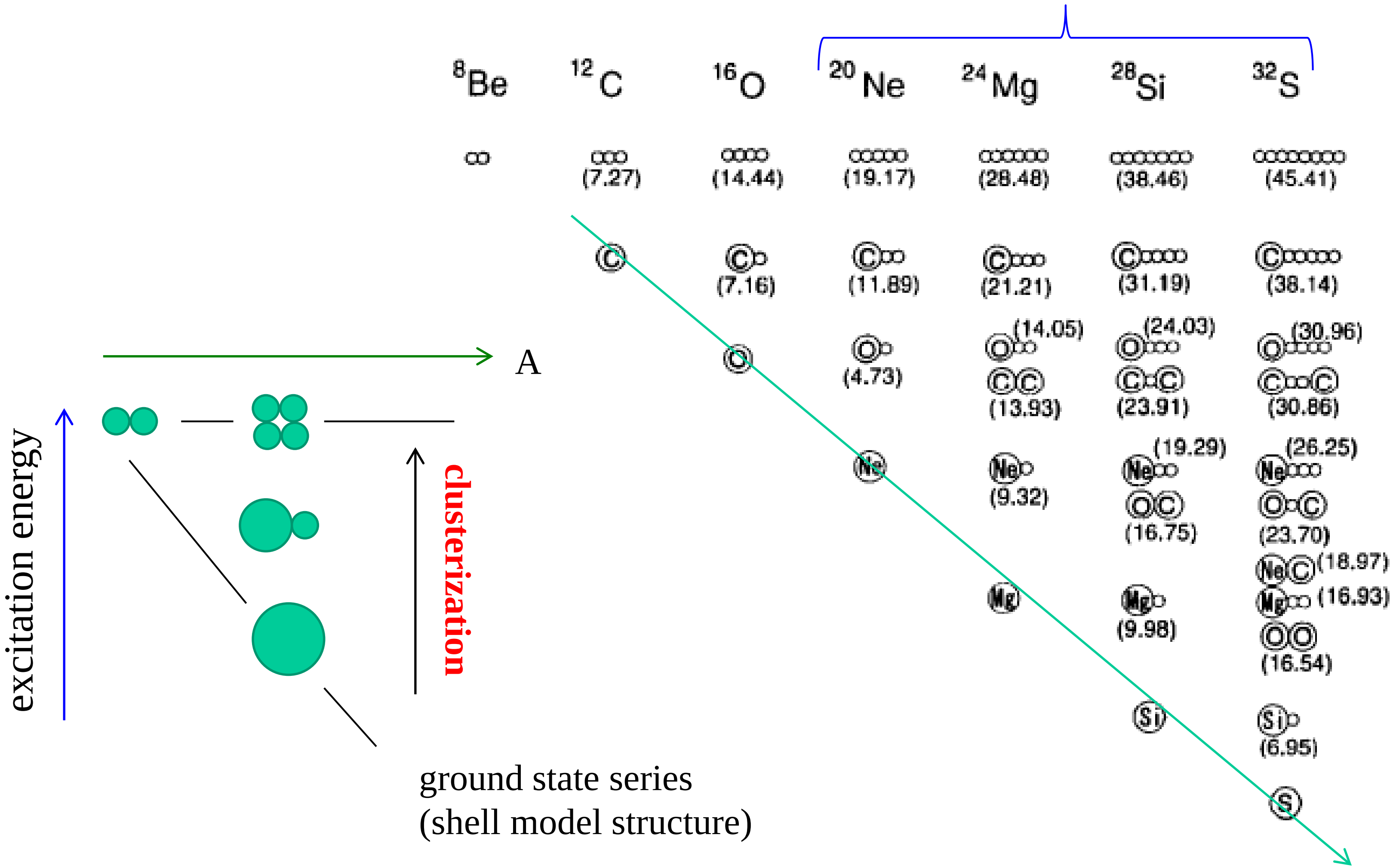


about 19% reduction of nuclear size
(shrinkage effect)

K. Tanida et al., PRL86('01)1982

How about heavier nuclei?

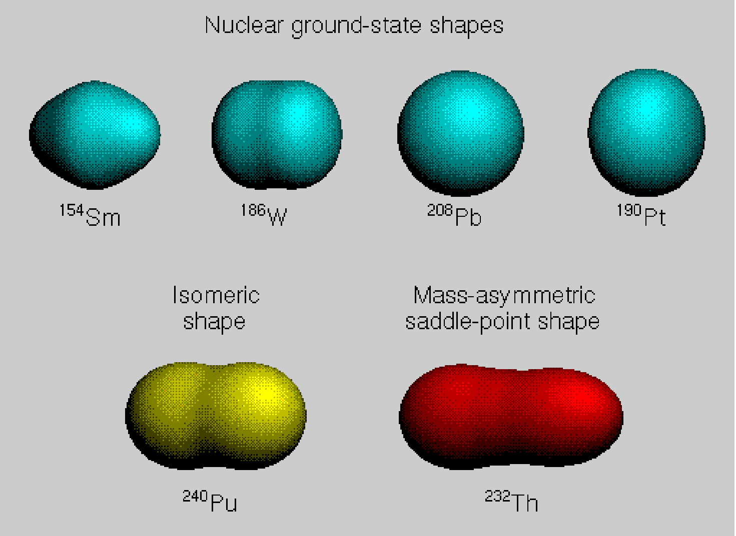
sd-shell nuclei Ikeda diagram

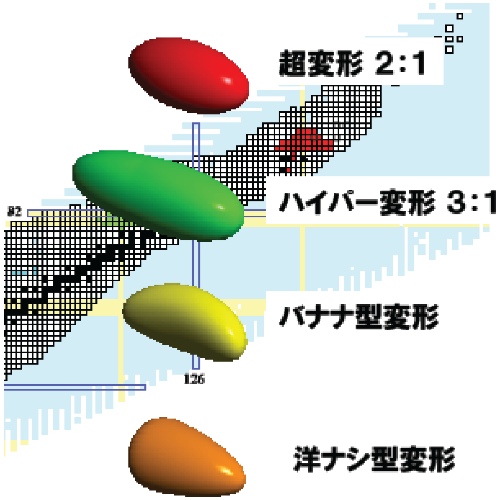


ground state : a shell model-like structure (for nuclei heavier than Be)

cluster-like structure: appears in the excited states (the threshold rule)

Shell model (mean-field) structure and nuclear deformation





http://t2.lanl.gov/tour/sch001.html

➢ many open-shell nuclei are deformed in the ground state

✓ characterstic feature of *finite* many-body systems

✓ spontaneous symmetry breaking of (rotational) symmetry

➢ B(E2) for deformed nuclei

$$B(E2: 2^+ \to 0^+) = \frac{1}{16\pi} \cdot Q_0^2$$

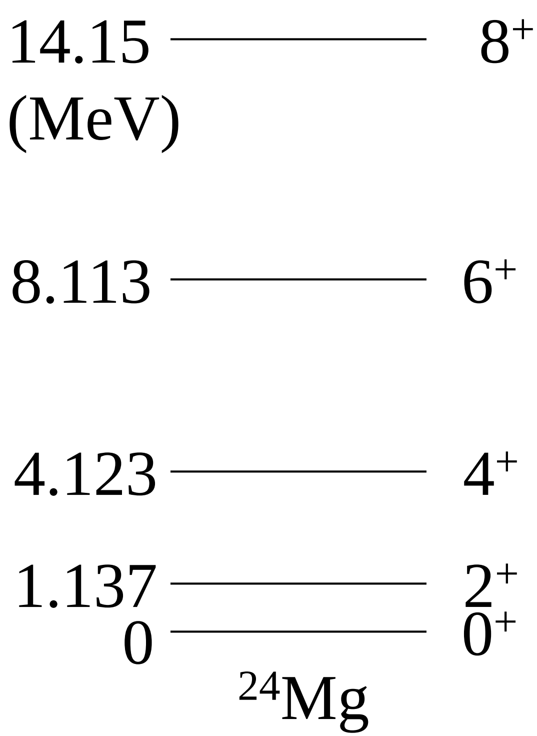
$$Q_0 \sim \sqrt{\frac{16\pi}{5}} \frac{3}{4\pi} Ze\, R_0^2\, \beta$$

A change in B(E2) can be interpreted as a change in β

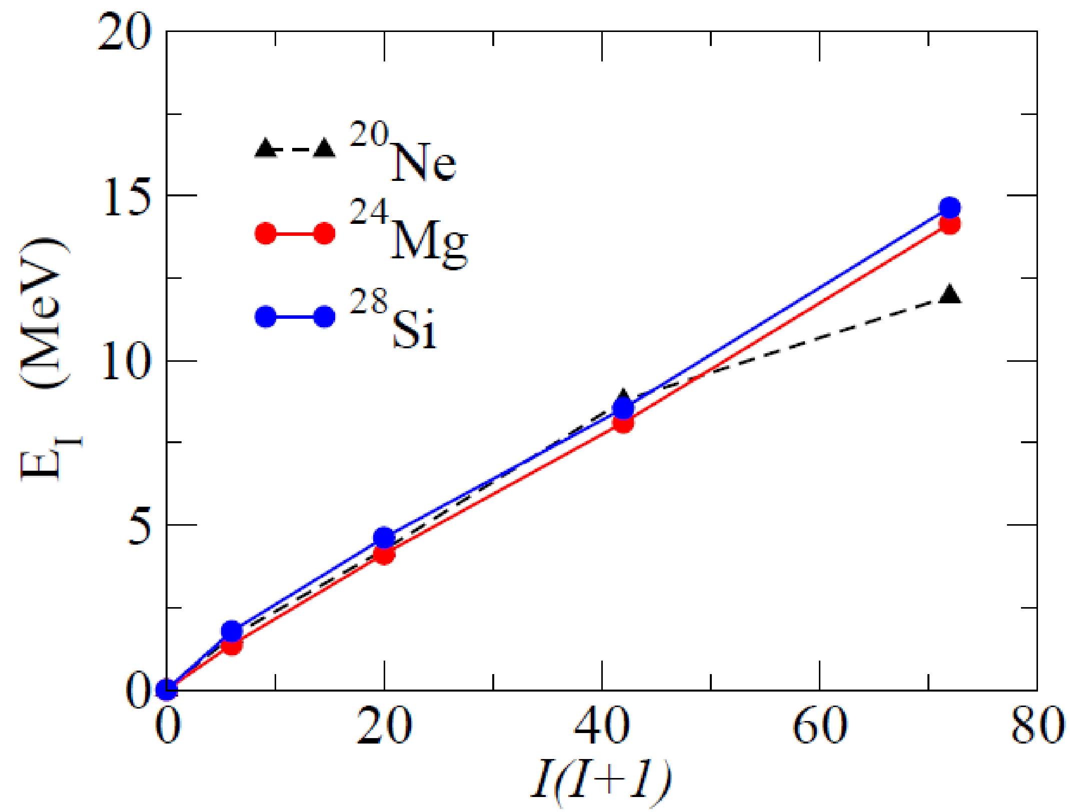
sd-shell nuclei : prominent nuclear deformation

an evidence for deformation

rotational spectrum

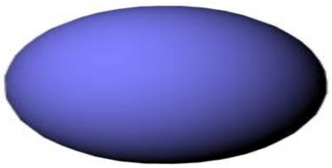


$$E_I \sim \frac{I(I+1)\hbar^2}{2\mathcal{J}}$$



How is the deformation altered due to an addition of Λ particle?

Self-consistent mean-field (Hartree-Fock) method:



independent nucleons in a mean-field potential

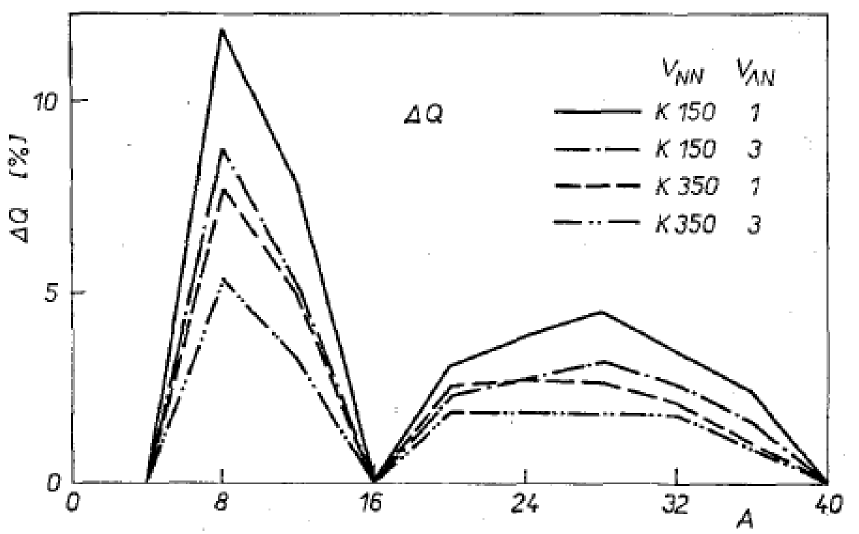
optimized shape can be automatically determined

= suitable for a discussion on shape of hypernuclei

➢ First application to deformed hypernucleus

J. Zofka, Czech. J. Phys. B30('80)95

Hartree-Fock calculations with V_{NN}: 3 range Gauss, $V_{\Lambda N}$: 2 range Gauss



Λ changes the Q-moment (deformation) at most by 5%

e.g., $\beta = 0.5 \longrightarrow \beta = 0.475$

Shape of hypernuclei

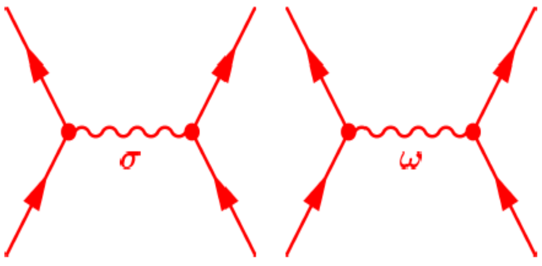
RMF for deformed hypernuclei

$$\mathcal{L} = \mathcal{L}_N + \bar{\psi}_\Lambda \left[\gamma_\mu \left(i\partial^\mu - g_{\omega\Lambda}\omega^\mu \right) - m_\Lambda - g_{\sigma\Lambda}\sigma \right] \psi_\Lambda$$

$$g_{\omega\Lambda} = \frac{2}{3} g_{\omega N} \longleftarrow \text{quark model}$$

$$g_{\sigma\Lambda} = 0.621 g_{\sigma N} \longleftarrow {}^{17}{}_{\Lambda}\mathrm{O}$$

cf. D. Vretenar et al., PRC57('98)R1060



Λσ and Λω couplings

variational principle

$$\begin{cases} \left[-i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla} + \beta\left(m_\Lambda + g_{\sigma\Lambda}\sigma(\boldsymbol{r})\right) + g_{\omega\Lambda}\omega^0(\boldsymbol{r}) \right] \psi_\Lambda = \epsilon_\Lambda \psi_\Lambda \\ \left[-\boldsymbol{\nabla}^2 + m_\omega^2 \right] \omega^0(\boldsymbol{r}) = g_\omega \rho_v(\boldsymbol{r}) + g_{\omega\Lambda} \psi_\Lambda^\dagger(\boldsymbol{r}) \psi_\Lambda(\boldsymbol{r}) \end{cases}$$

etc.

→ self-consistent solution (iteration)

RMF for deformed hypernuclei

self-consistent solution (iteration)

→ (intrinsic) Quadrupole moment

$$Q = \sqrt{\frac{16\pi}{5}} \int d\boldsymbol{r} \, [\rho_v(\boldsymbol{r}) + \psi^\dagger_\Lambda(\boldsymbol{r})\psi_\Lambda(\boldsymbol{r})] \, r^2 Y_{20}(\hat{\boldsymbol{r}})$$

Application to hypernuclei

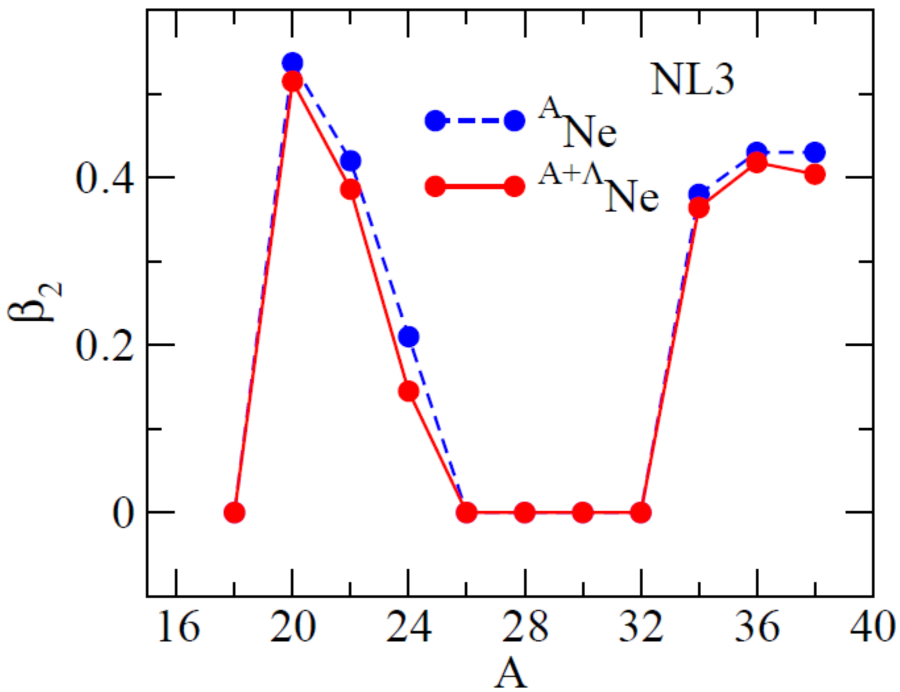
- parameter sets: NL3 and NLSH
- **Axial symmetry**
- pairing among nucleons: Const. gap approach

  $\Delta_n = 4.8/N^{1/3}$ $\Delta_p = 4.8/Z^{1/3}$ (MeV)
- **Λ particle: the lowest s.p. level ($K^\pi = 1/2^+$)**
- Basis expansion with deformed H.O. wf
- Deformation parameter:

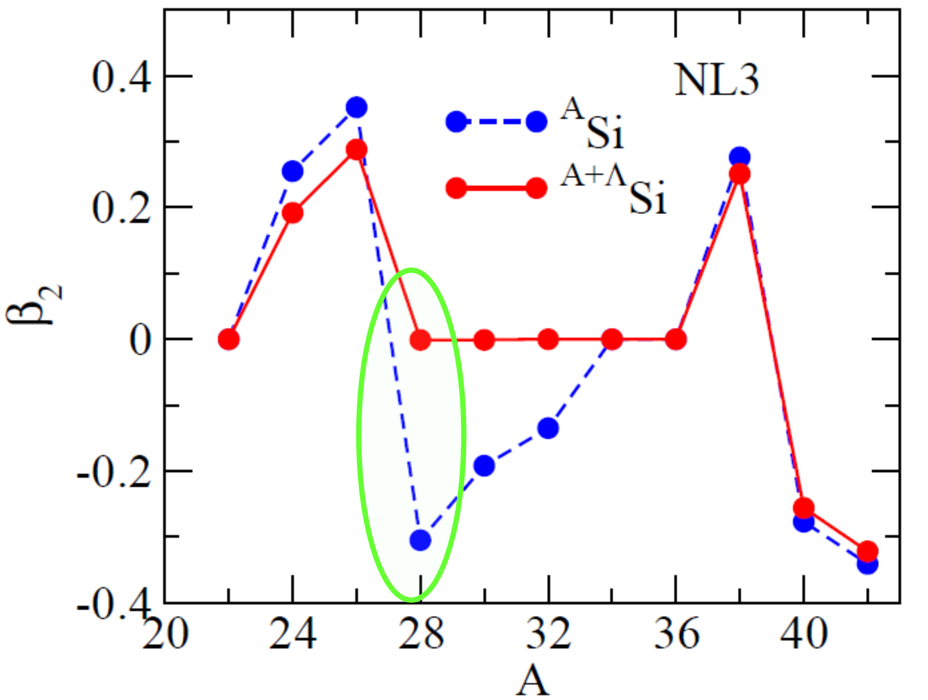
$$Q = \sqrt{\frac{16\pi}{5}} \frac{3}{4\pi} (A_c + 1) R_0^2 \beta$$

$$R_0 = 1.2 \, A_c^{1/3} \text{ (fm)}$$

Ne isotopes



Si isotopes



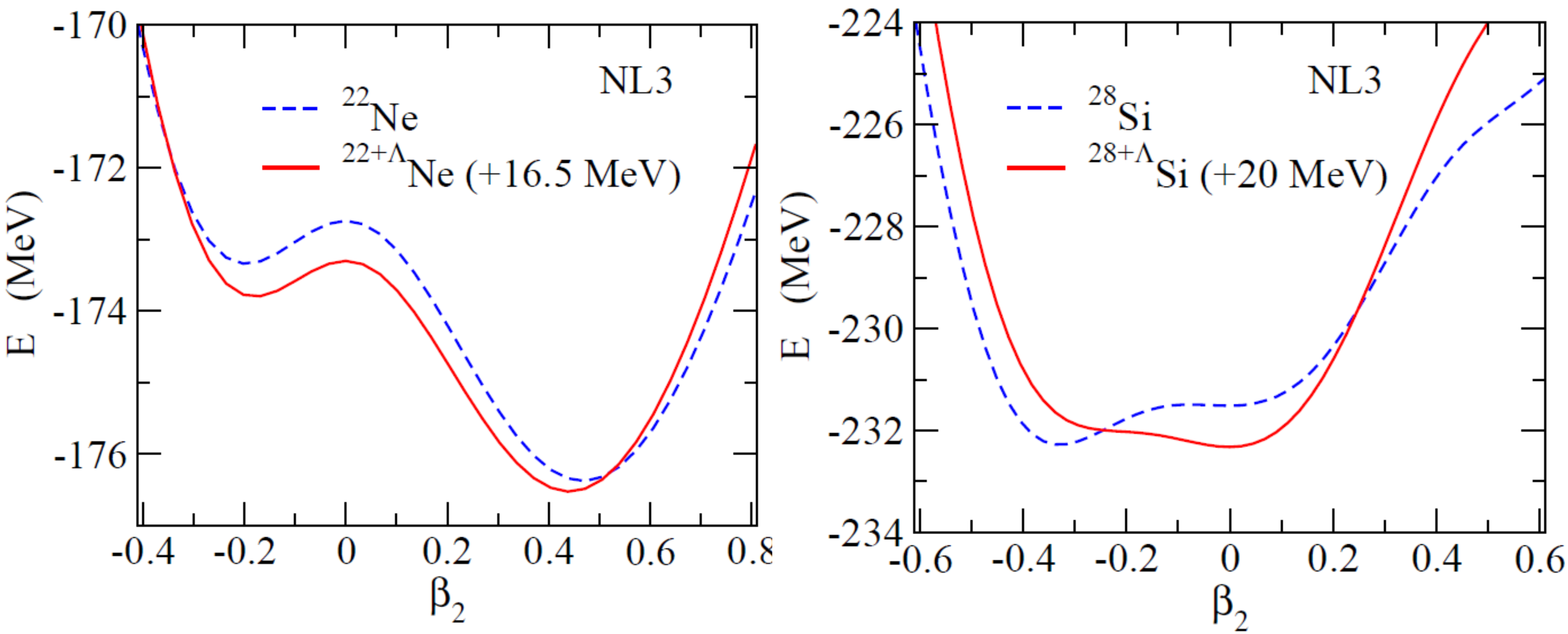
- in most cases, similar deformation between the core and the hypernuclei
- hypernuclei: slightly smaller deformation than the core

Exception: $^{29}{}_{\Lambda}$Si

oblate (^{28}Si) $\xrightarrow{\Lambda}$ spherical ($^{29}{}_{\Lambda}$Si)

Myaing Thi Win and K.H., PRC78('08)054311

Potential energy surface (constraint Hartree-Fock)



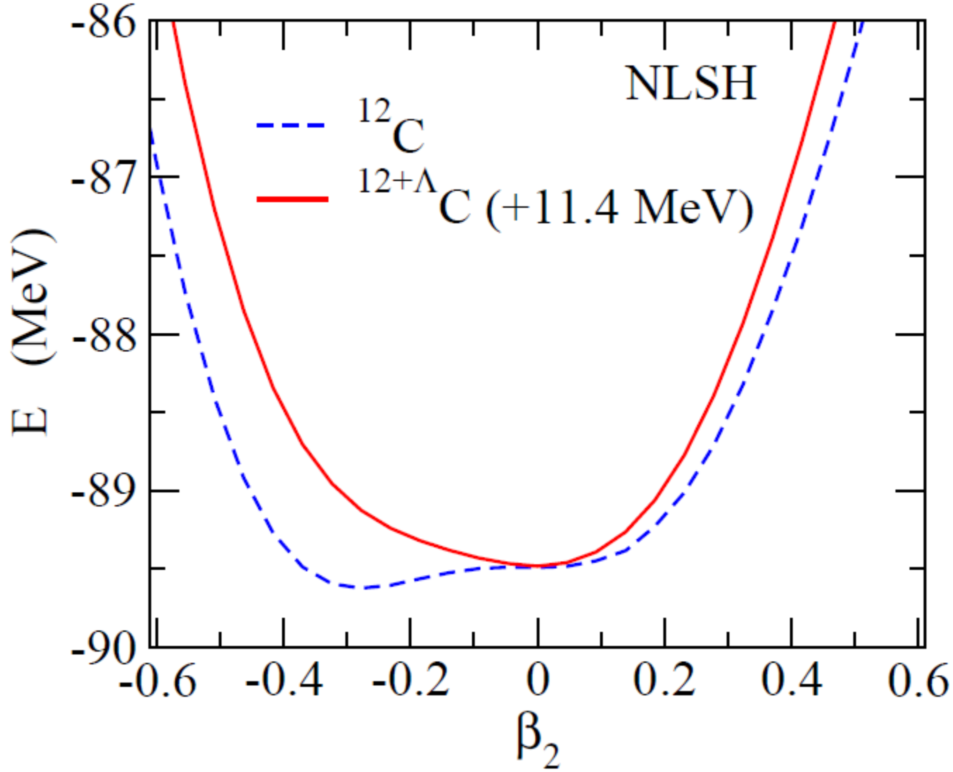
a flat energy curve

⟶ a large change in nuclear deformation due to a Λ particle

the same conclusion also with NLSH
and/or with constant G approach to pairing

Myaing Thi Win and K.H., PRC78('08)054311

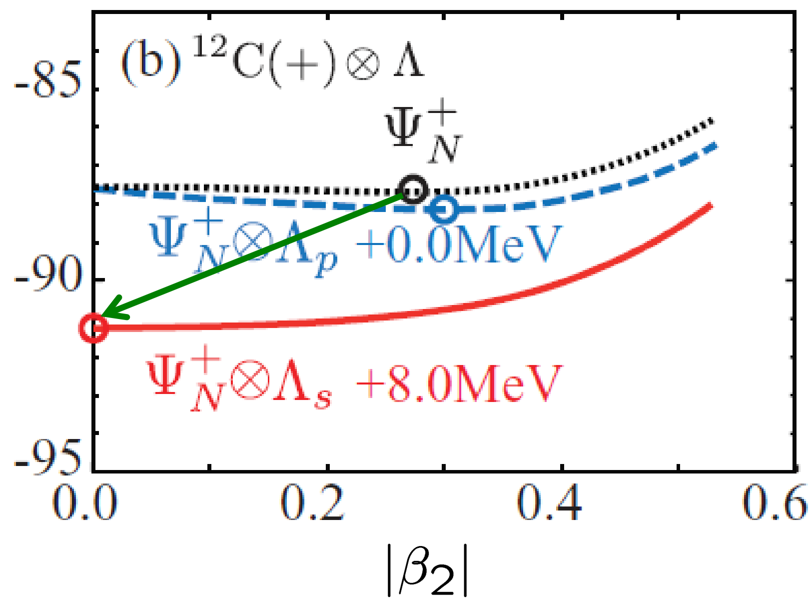
Another example: $^{13}{}_{\Lambda}C$



oblate ⟶ spherical

Myaing Thi Win and K.H.,
PRC78('08)054311

cf. recent AMD calculations



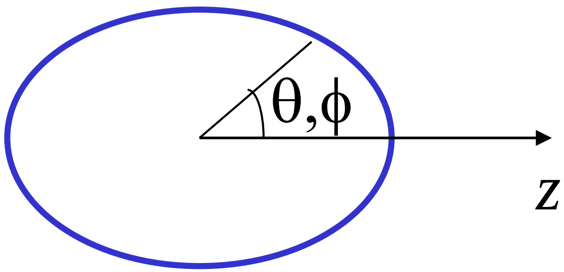
M. Isaka, K. Kimura, A. Dote,
and A. Ohnishi, PRC83('11)044323

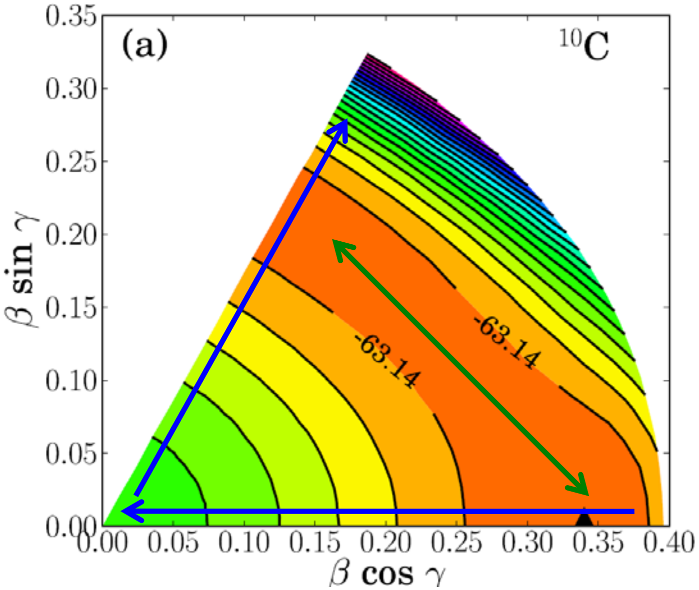
3D Hartree-Fock calculation for hypernuclei

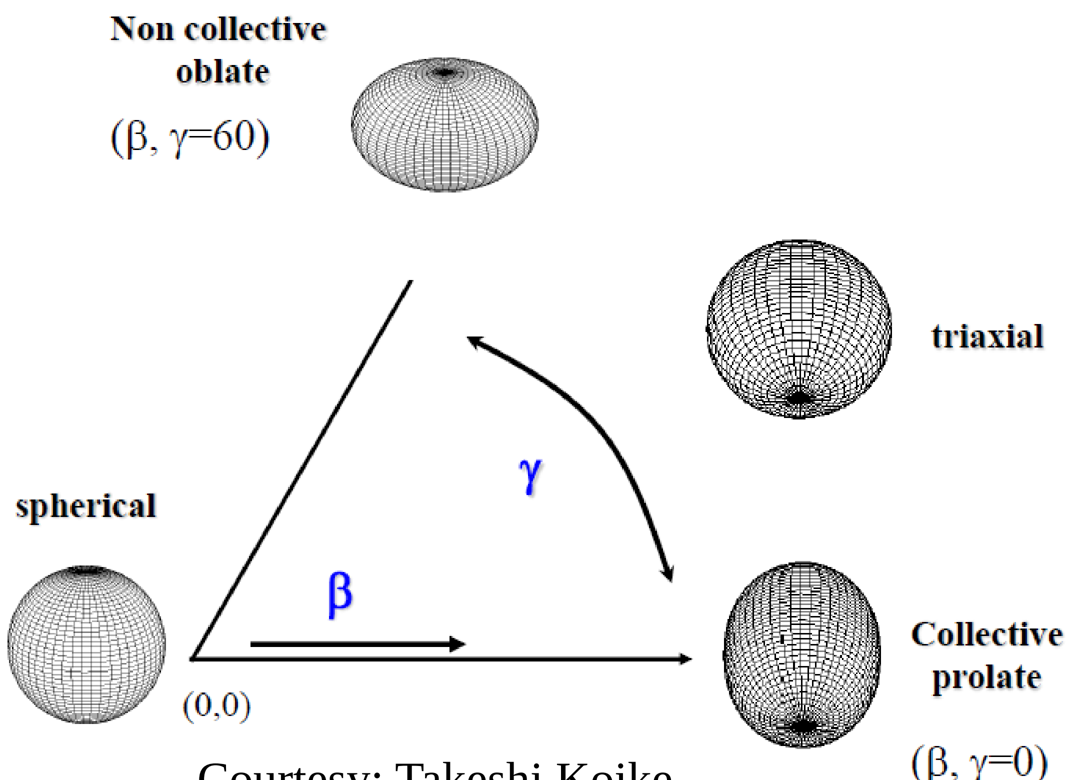
So far, axial symmetric shape has been assumed for simplicity

→ Effect of Λ particle on triaxial deformation?

$$R(\theta,\phi) = R_0\left[1+\beta\cos\gamma Y_{20}(\theta)+\frac{1}{\sqrt{2}}\beta\sin\gamma(Y_{22}(\theta,\phi)+Y_{2-2}(\theta,\phi))\right]$$







Courtesy: Takeshi Koike

Skyrme-Hartree-Fock calculations for hypernuclei

3D calcaulations with non-relativistic Skyrme-Hartree-Fock:
the most convenient and the easiest way

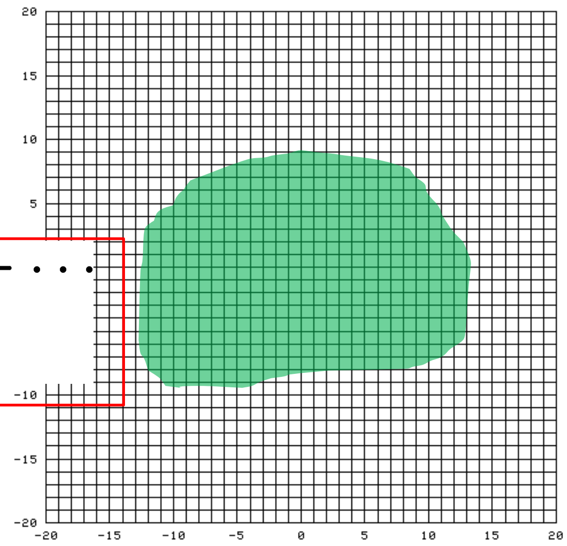
- zero-range interaction
- 3D mesh calculation (“lattice Hartree-Fock”)
- Imaginary time evolution of single-particle wave functions
- computer code “ev8” available

  P. Bonche, H. Flocard, and P.-H. Heenen,
  NPA467(‘87)115, CPC171(‘05)49

⇨ extension to hypernuclei

$$
\begin{aligned}
v_{\Lambda N}(\boldsymbol{r}_\Lambda, \boldsymbol{r}_N) &= t_0(1 + x_0 P_\sigma)\delta(\boldsymbol{r}_\Lambda - \boldsymbol{r}_N) + \cdots \\
v_{\Lambda NN}(\boldsymbol{r}_\Lambda, \boldsymbol{r}_1, \boldsymbol{r}_2) &= t_3\delta(\boldsymbol{r}_\Lambda - \boldsymbol{r}_1)\delta(\boldsymbol{r}_\Lambda - \boldsymbol{r}_2)
\end{aligned}
$$

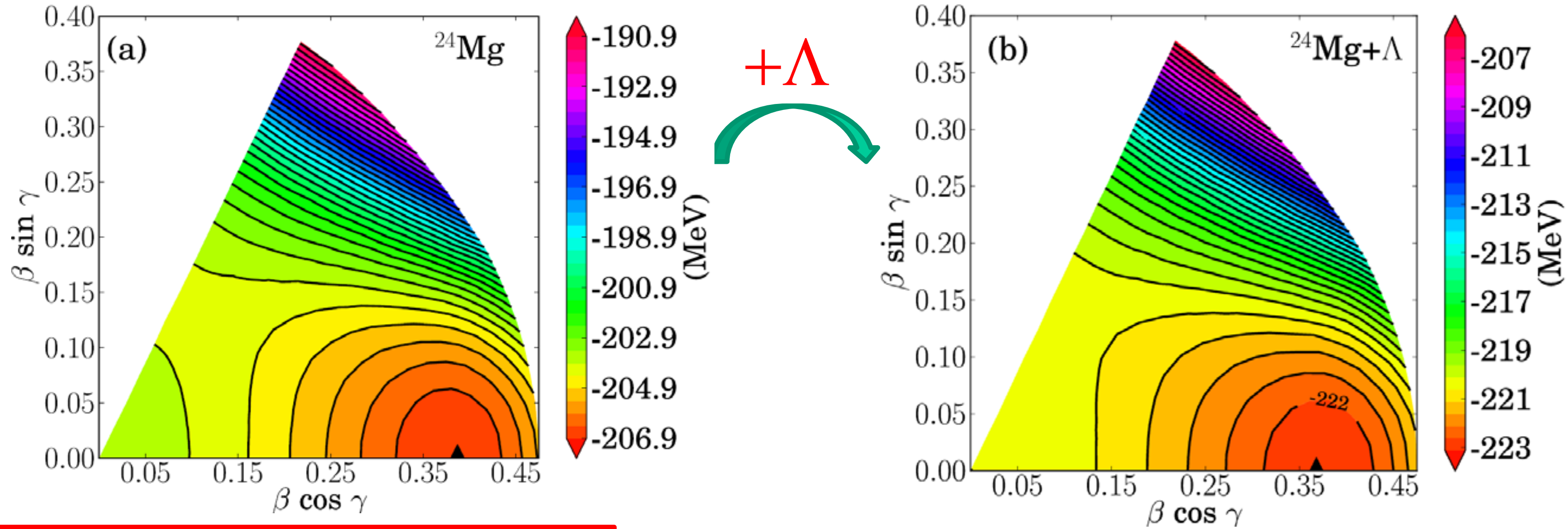
M. Rayet, NPA367(‘81)381



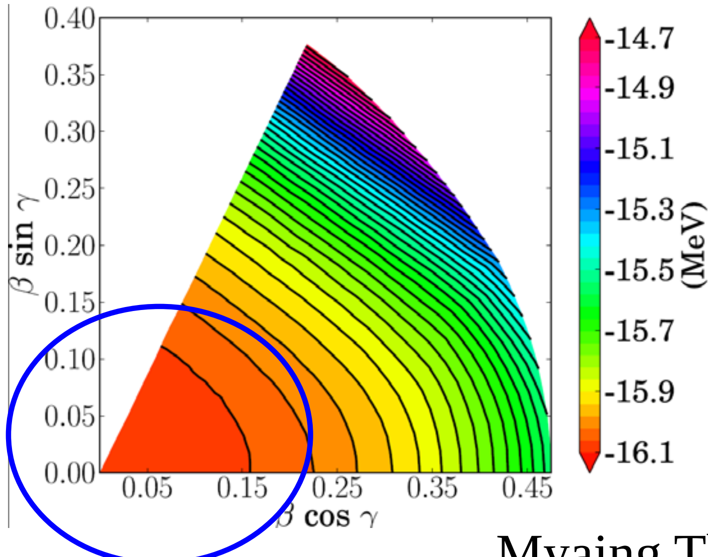
c.f. axially symmetric SHF calculations:

X.-R. Zhou *et al.*, PRC76(‘07) 034312

^{24}Mg, $^{25}{}_{\Lambda}$Mg (Interaction No.1 of Yamamoto *et al.* + SGII (NN))



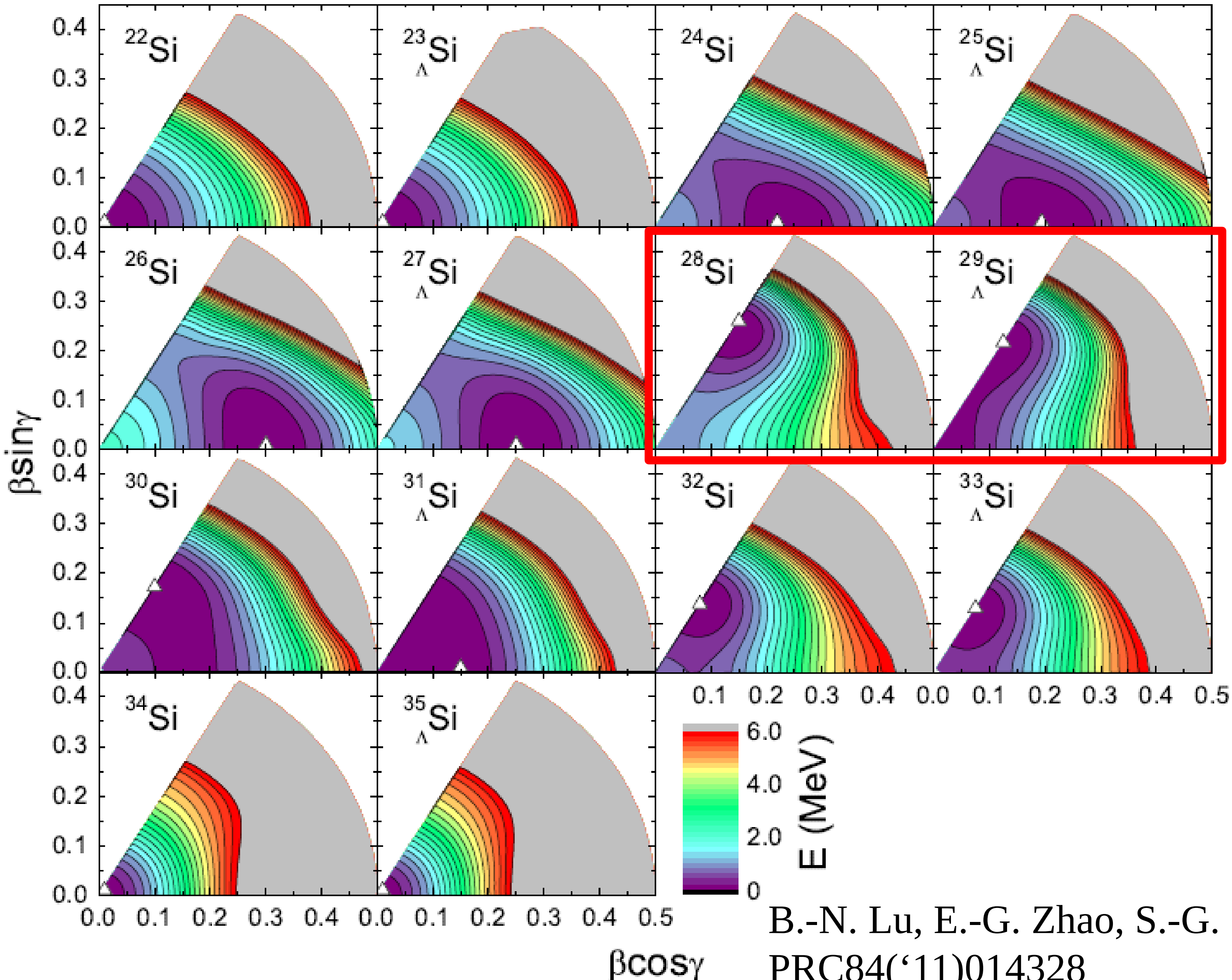
$$E_{{}^{25}_{\Lambda}Mg}(\beta,\gamma) - E_{{}^{24}Mg}(\beta,\gamma)$$



- Deformation is driven to speherical when Λ is in the lowest state
- Prolate configuration is prefered for the same value of β

Myaing Thi Win, K.H., T. Koike, Phys. Rev. C83('11)014301

c.f. 3D RMF calculations



B.-N. Lu, E.-G. Zhao, S.-G. Zhou, PRC84('11)014328

Rotational Excitation of Λ hypernuclei

Collective spectrum of a single-Λ hypernucleus: a half-integer spin

"Bohr Hamiltonian" for the *core* part:

$$\mathcal{H}_{\rm coll} = T_{\rm vib} + \frac{1}{2}\sum_{k=1}^{3}\frac{\hat{I}_k^2}{2\mathcal{J}_k} + V_{\rm coll}(\beta,\gamma)$$

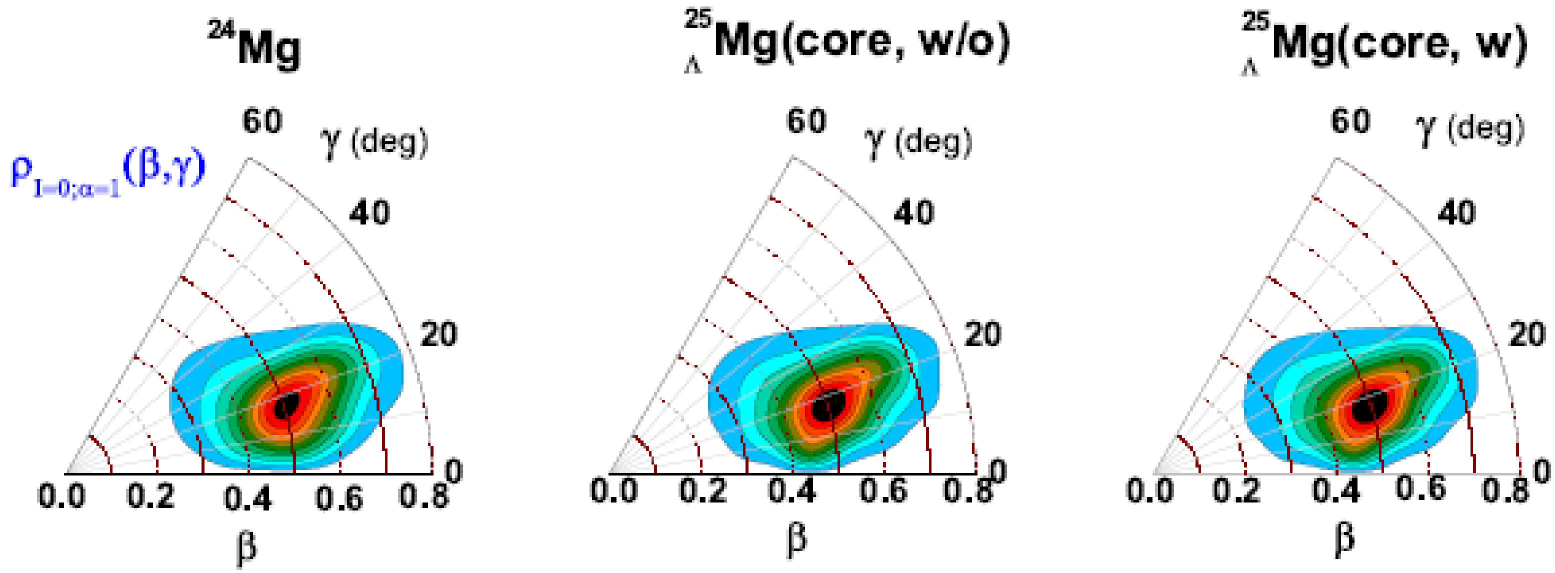
mass inertias: cranking approximation

(Inglis-Belyaev formula for the rotational inertia)

$$V_{\rm coll}(\beta,\gamma) = E(\beta,\gamma) - \Delta V_{\rm vib}(\beta,\gamma) - \Delta V_{\rm rot}(\beta,\gamma)$$

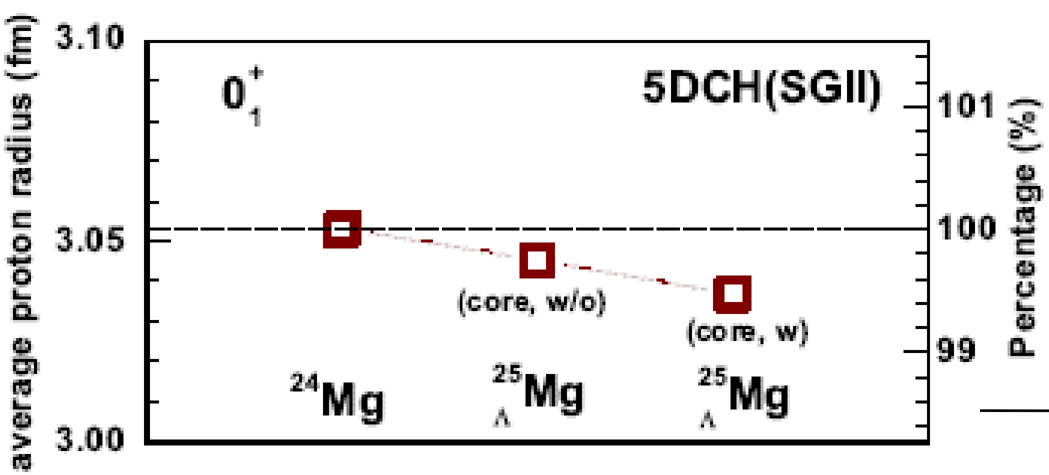
$$\begin{cases} (i)\;\; E(\beta,\gamma) = E_N(\beta,\gamma) \\ (ii)\;\; E(\beta,\gamma) = E_N(\beta,\gamma) + \int d\boldsymbol{r}\,\mathcal{E}_{N\Lambda}(\boldsymbol{r}) \end{cases}$$

Solution of Collective H ⟶ fluctuation of deformation parameters



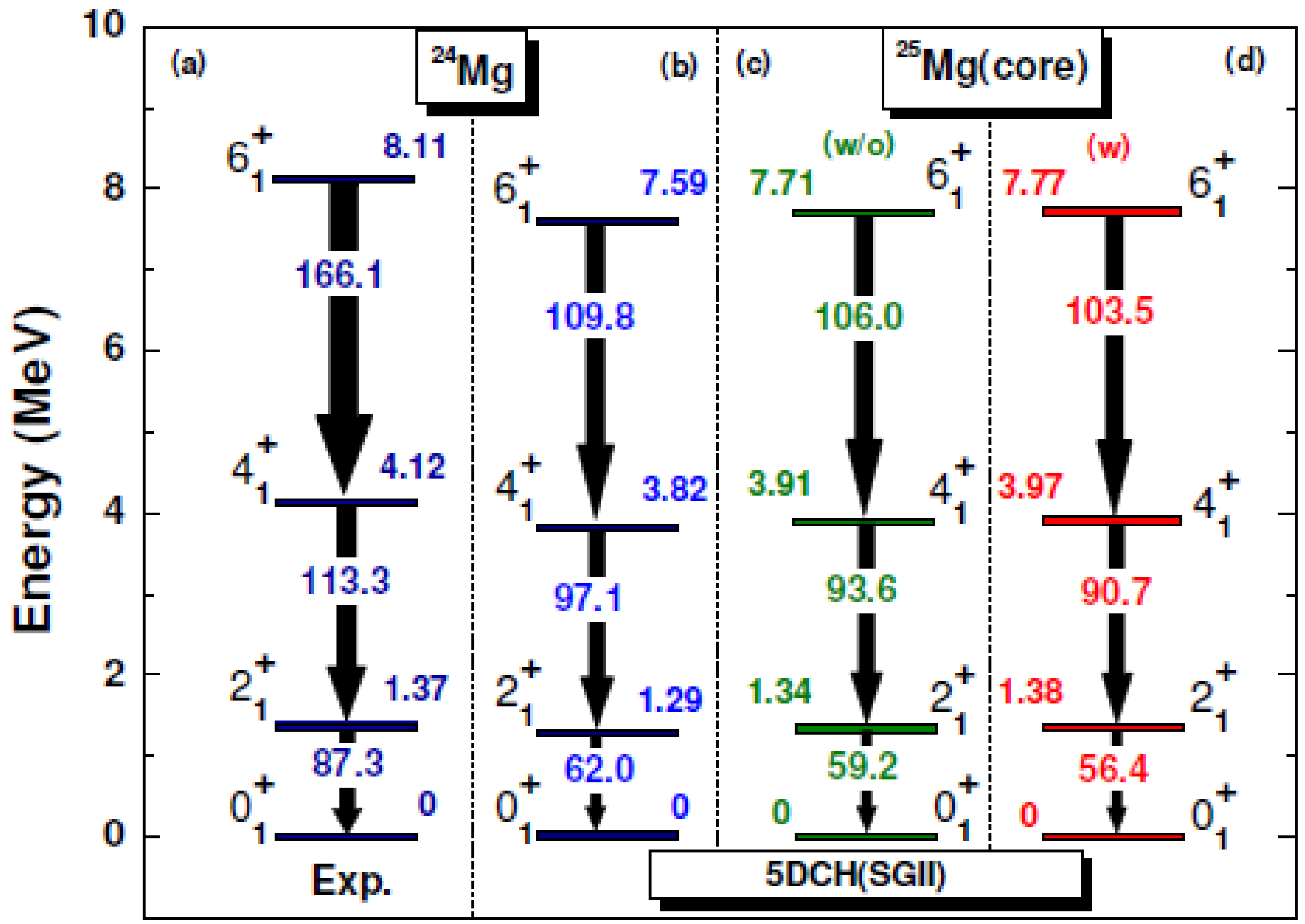
$$\langle\beta\rangle = 0.54$$
$$\langle\gamma\rangle = 20^\circ$$

$$\langle\beta\rangle = 0.52$$
$$\langle\gamma\rangle = 20.8^\circ$$



J.M. Yao, Z.P. Li, K.H. et al., NPA868-869('11)12

⟶ much smaller change



J.M. Yao, Z.P. Li, K.H. et al., NPA868-869('11)12

reduction of B(E2) from 2^+ to 0^+

^{24}Mg: B(E2) = 62.0 e^2fm^4

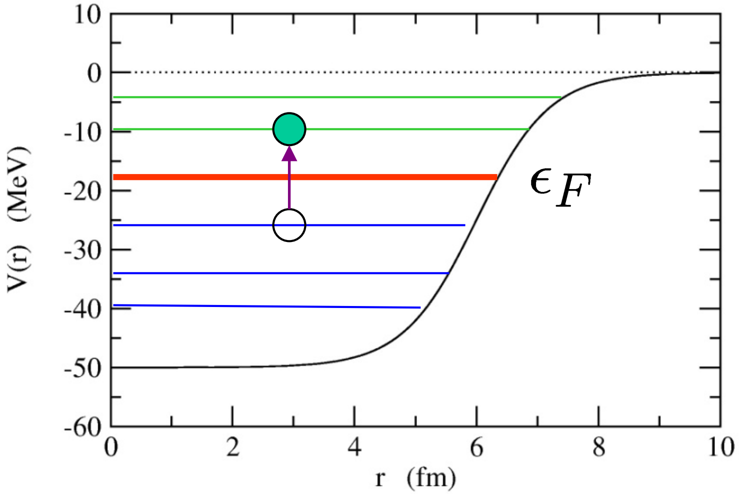
$^{25}{}_{\Lambda}$Mg: B(E2) = 56.4 e^2fm^4 (about 9% reduction)

cf. AMD calculation for $^{25}{}_{\Lambda}$Mg (M. Isaka et al., PRC85('12)034303)

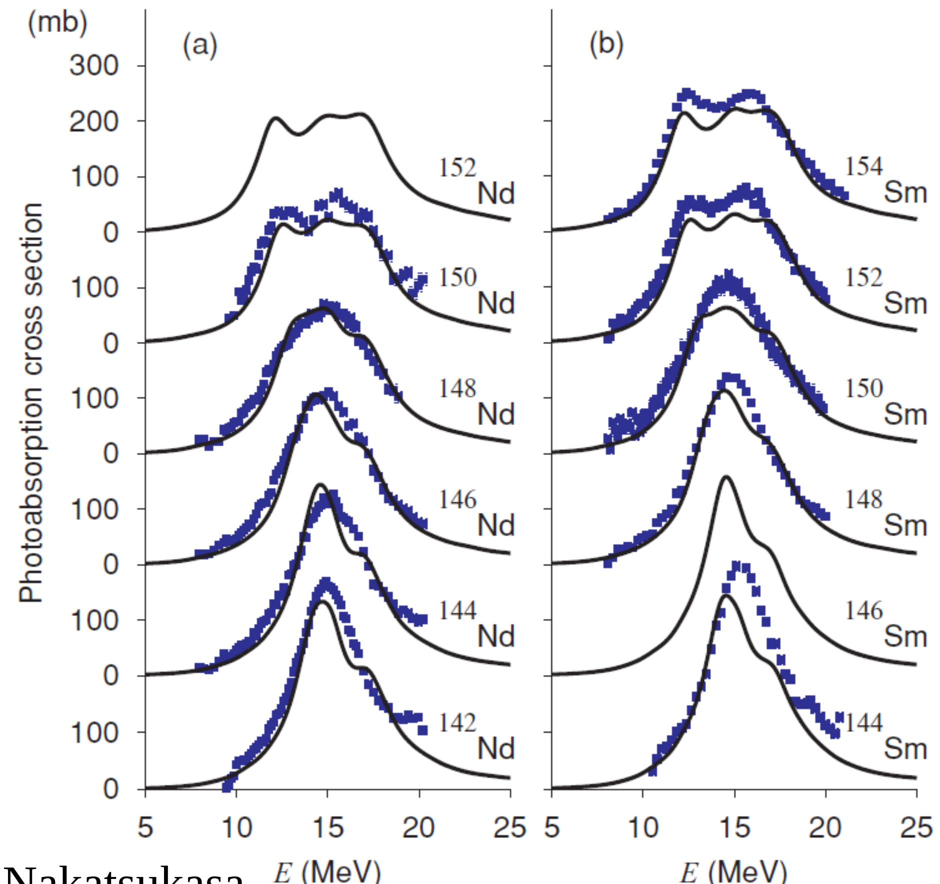
Vibrational Excitation of spherical Λ hypernuclei

RPA: linear superposition of many 1p1h sates →

✓low-lying collective motions
✓Giant Resonances
of ordinary nuclei



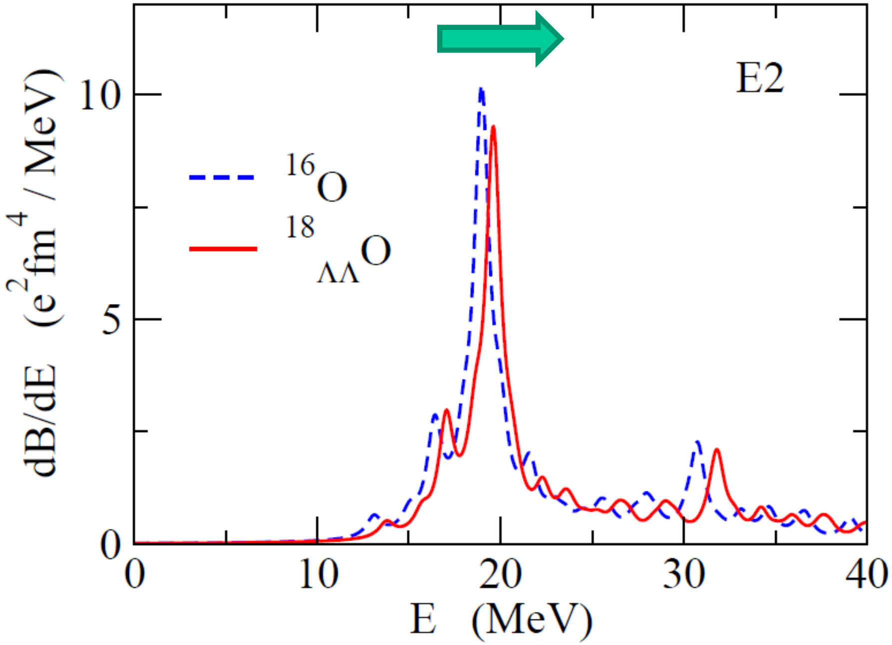
$$\sum_{ph}(X_{ph}a_p^\dagger a_h - Y_{ph}a_h^\dagger a_p)|HF\rangle$$

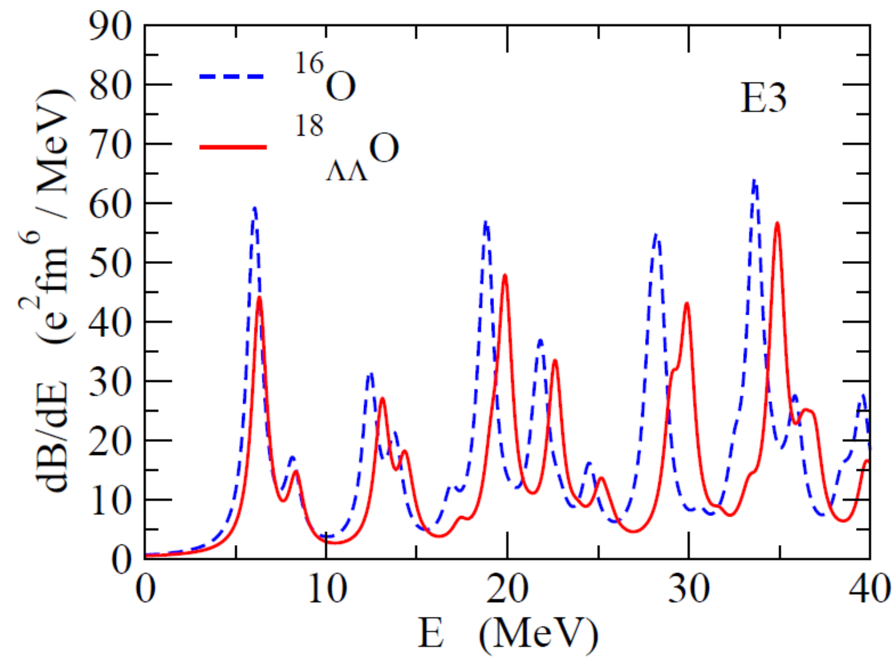


K. Yoshida and T. Nakatsukasa, PRC83('11)021304(R)

Application to $^{18}_{\Lambda\Lambda}O$

Skyrme HF + RPA
SkM* + Yamamoto No. 5 + Lanskoy SΛΛ1



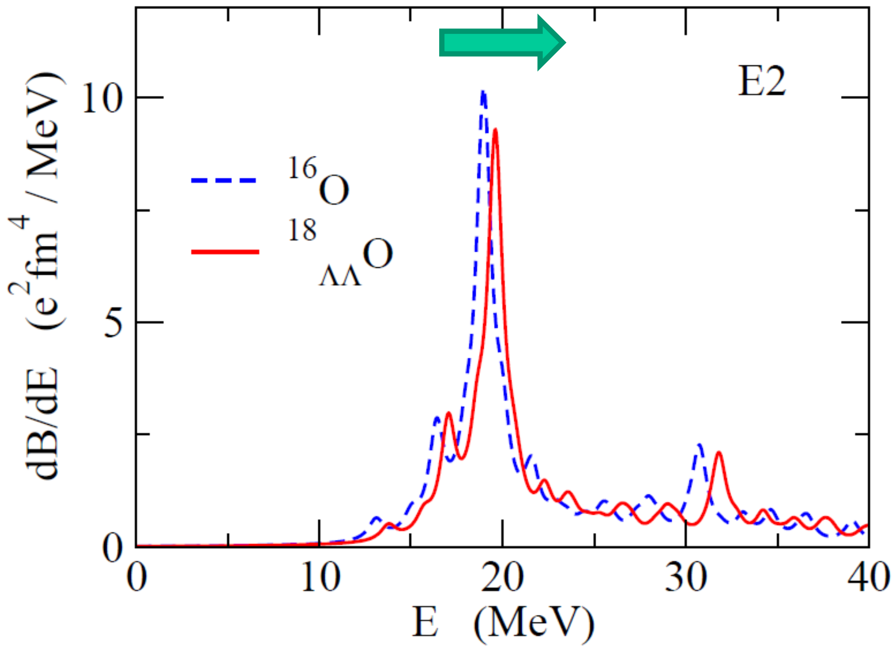


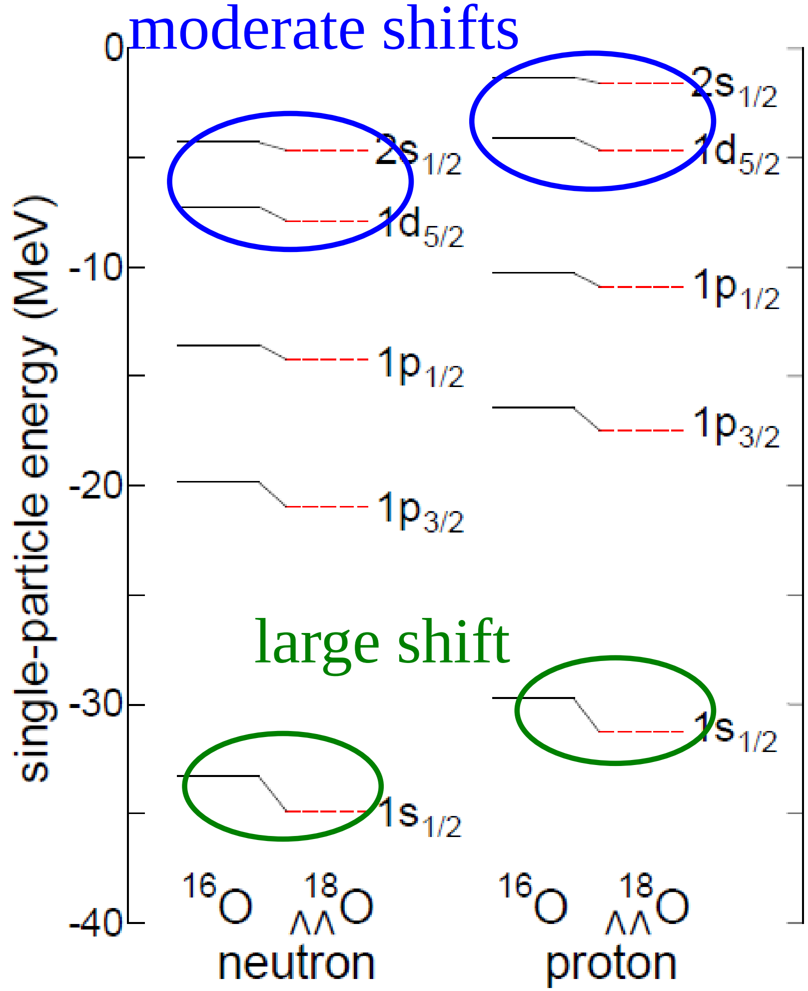
low-lying collective states

	2_1^+		3_1^-	
nucleus	*E* (MeV)	*B*(E2) (e^2fm^4)	*E*(MeV)	*B*(E3) (e^2fm^6)
^{16}O	13.1	0.726	6.06	91.1
$^{18}_{\Lambda\Lambda}$O	13.8	0.529	6.32	67.7

F. Minato and K.H., PRC85('12)924316

shifts toward
high energy





low-lying collective states

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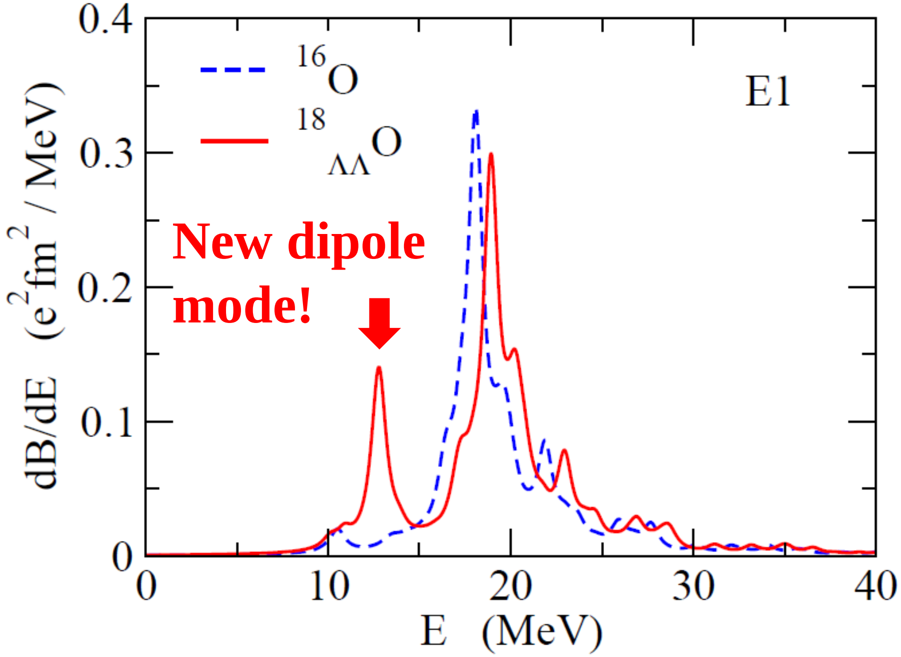
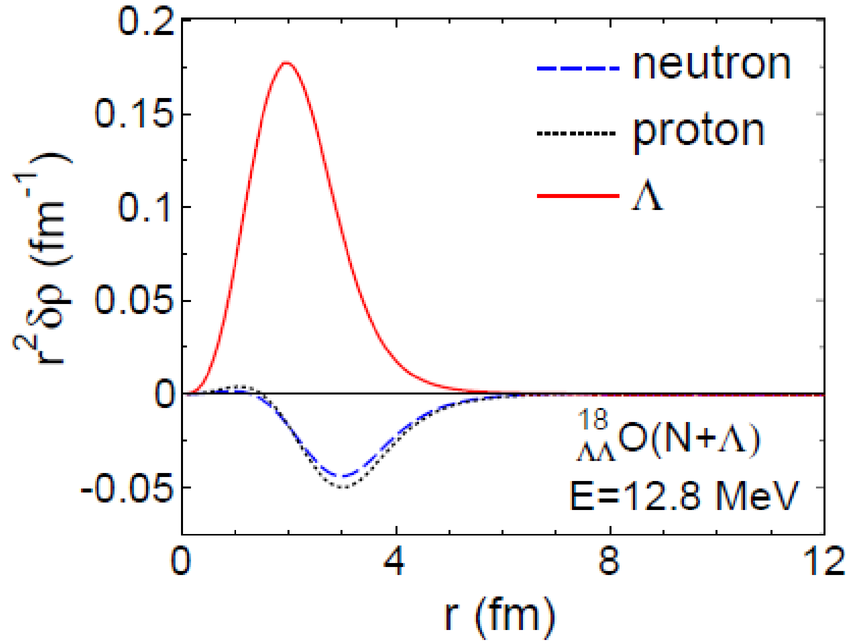
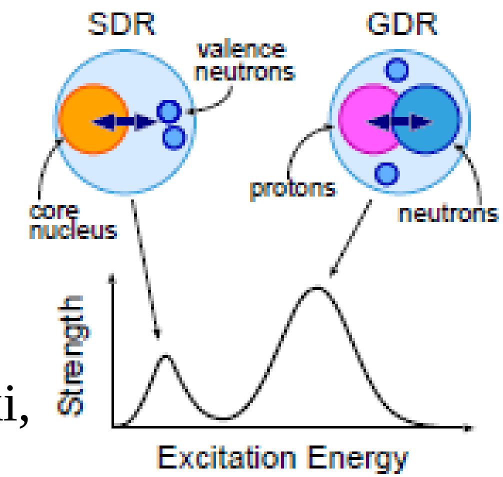
Dipole motion



dipole motion of Λ particles around the core nucleus

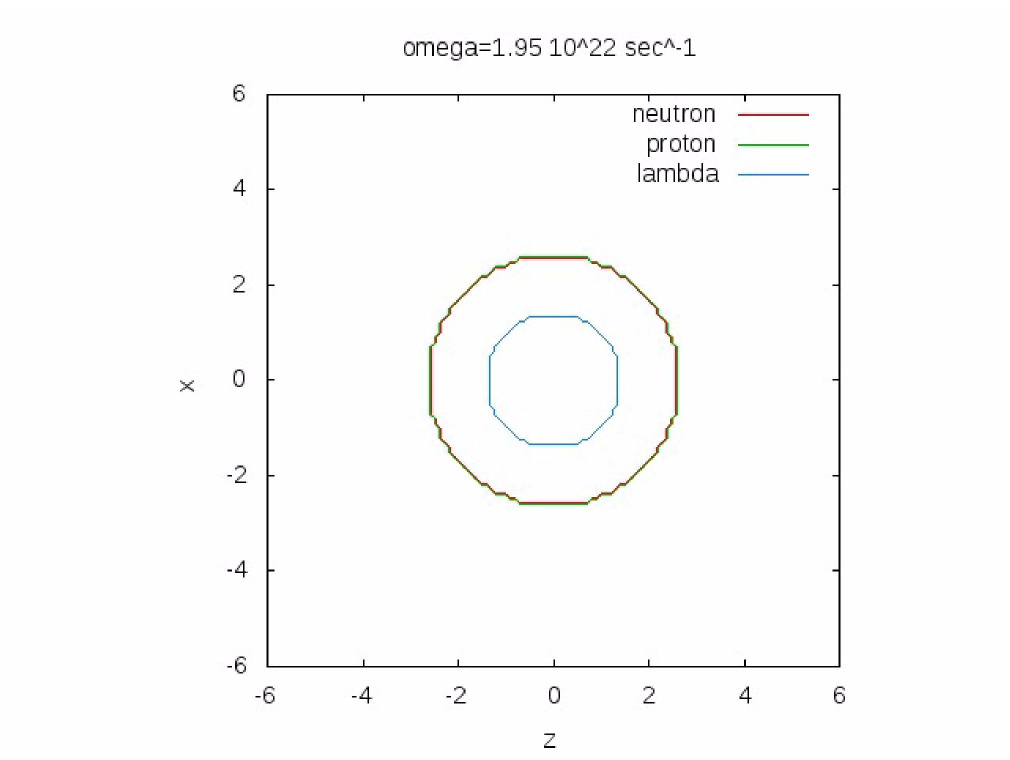


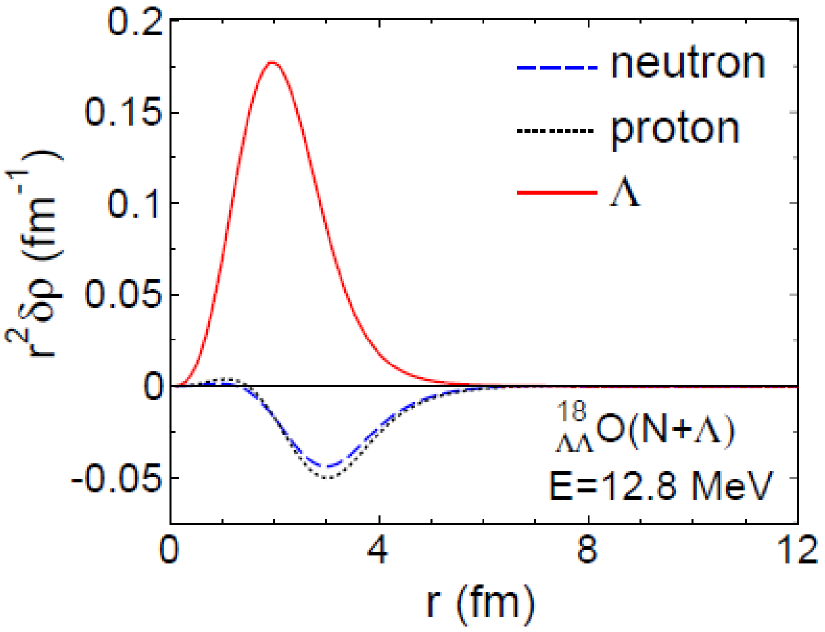
cf. soft dipole motion in neutron-rich nucleus



K. Ikeda, T. Myo, K. Kato, and H. Toki, Lecture Note in Phys., vol. 818

$$\rho(\boldsymbol{r},t) = \rho_0(r) + \delta\rho(\boldsymbol{r}) Y_{1\mu}(\hat{\boldsymbol{r}}) \sin(\omega t)$$





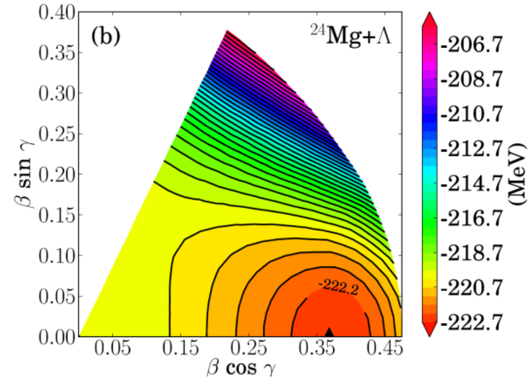
Summary

Shape of Λ hypernuclei: from the view point of mean-field theory

- deformation: an important key word in the sd-shell region
- RMF: stronger influence of Λ particle

  ⟶ Shape of ^{28}Si : drastically changed due to Λ
- SHF: weaker influence of Λ, but large def. change if PES is very flat

  - 3D calcaulations
  - softening of γ-vibration?



Rotational excitations of Λ hypernuclei

- about 9% reduction of B(E2) value for ^{24}Mg

Vibrational excitations of Λ hypernuclei

- **New dipole mode**

A challenging problem

- full spectrum of a single Λ hypernucleus

  odd mass, broken time reversal symmetry, half-integer spins