Particle-rotation/vibration couplings in hypernuclei

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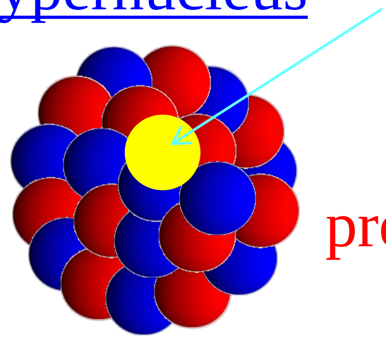
1. *Introduction: hypernuclei*
2. *Microscopic particle-core coupling schemes for hypernuclei*
3. *Spectrum of Λ hypernuclei*
4. *Summary*

"Recent progress of nuclear structure and reaction theory", Tohoku University, 2018.4.25-26

Introduction

Λ hypernucleus

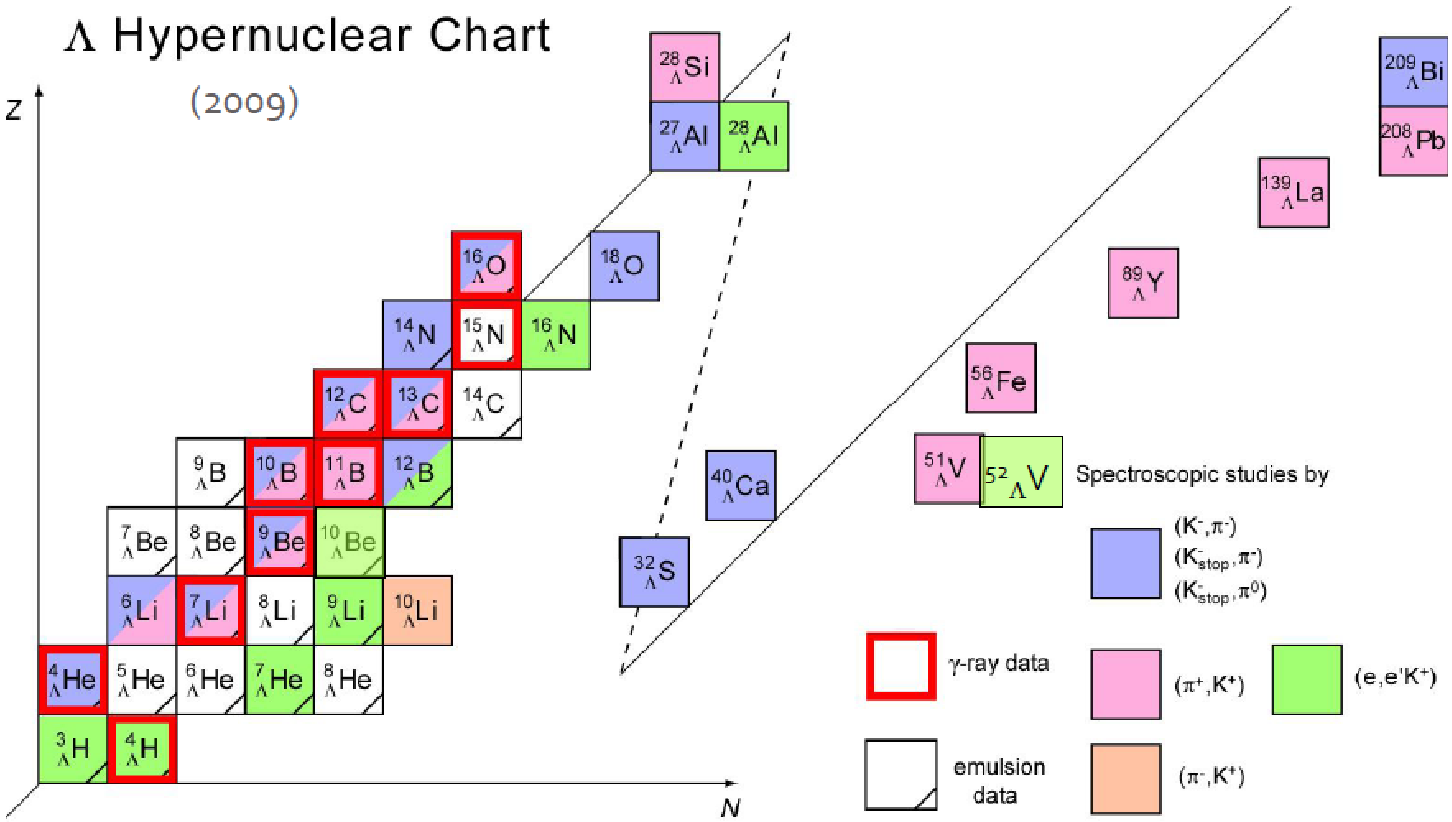


proton

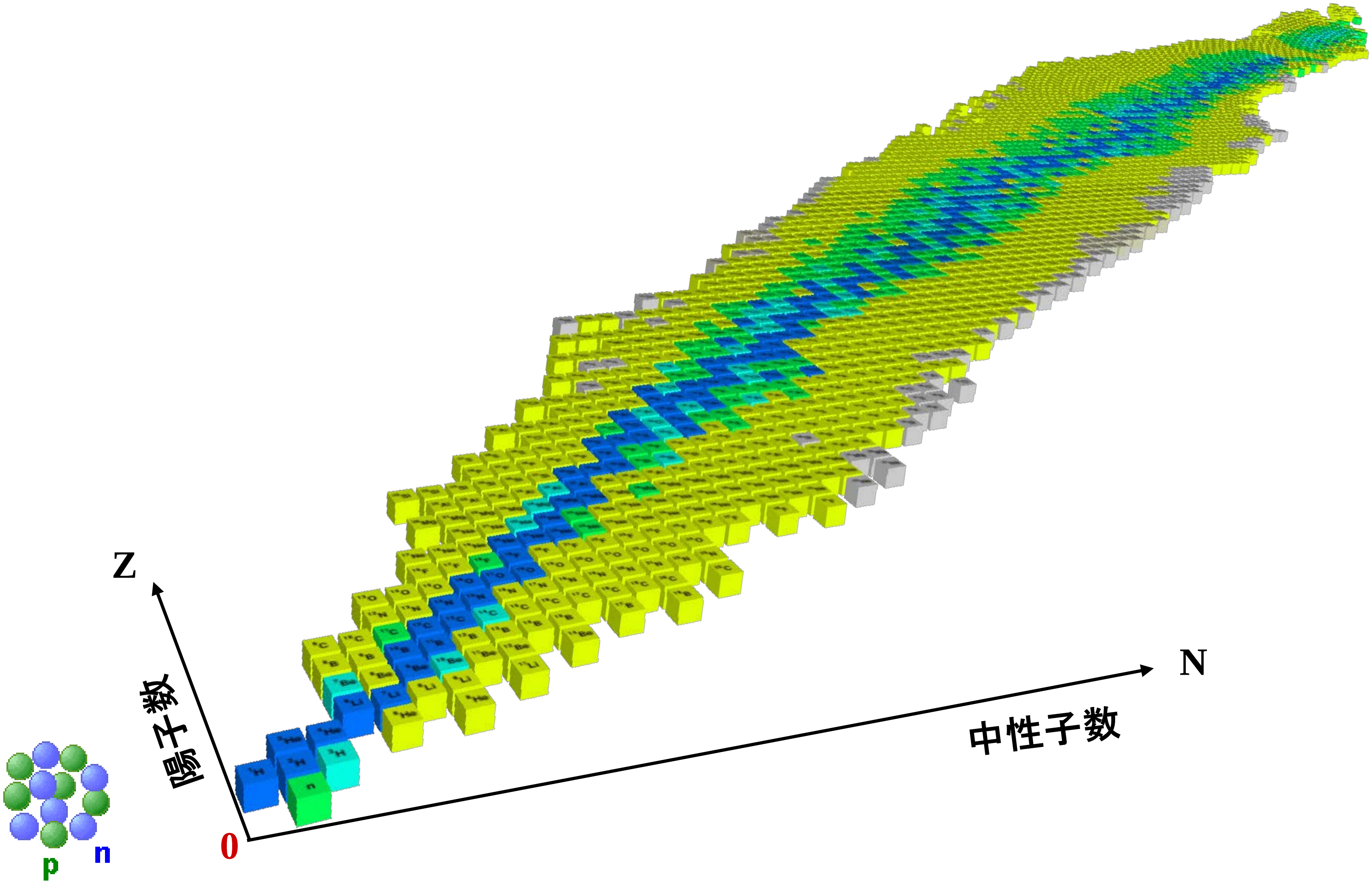
neutron

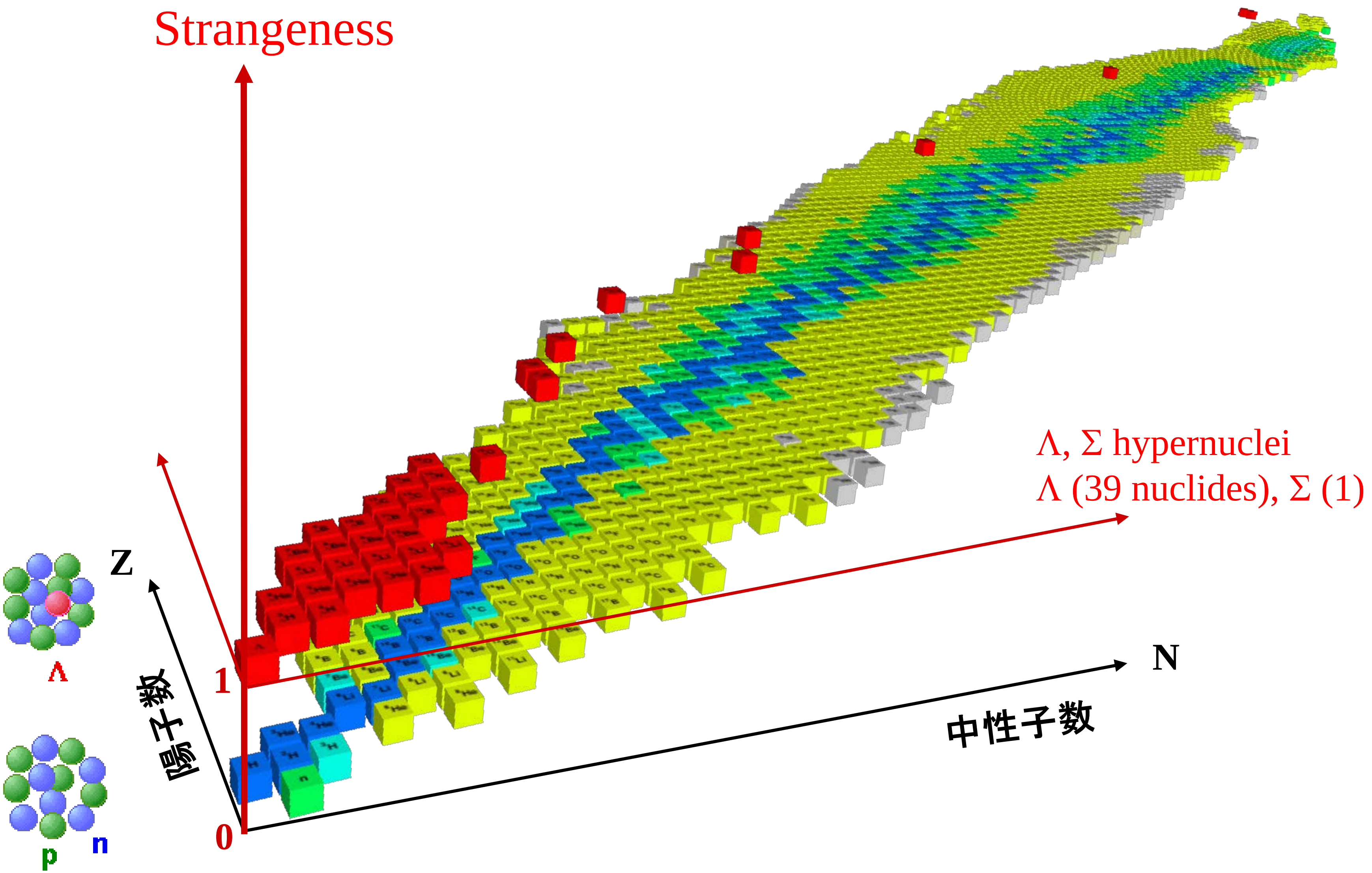
Λ particle: the lightest hyperon
(no charge, no isospin)

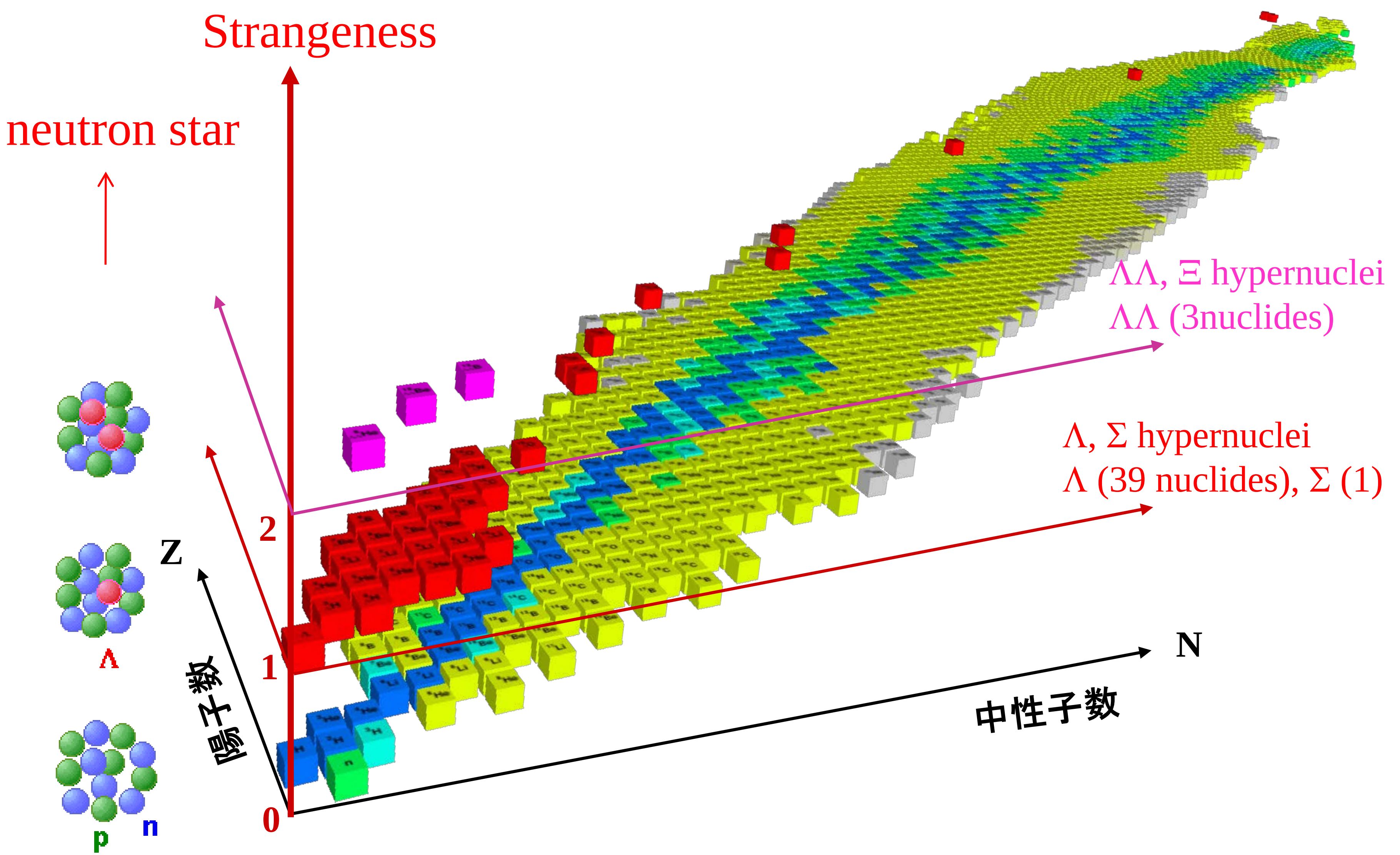
*no Pauli principle between nucleons and a Λ particle



O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57('06)564


Z
陽子数
N
中性子数
0
p
n


Strangeness
Λ, Σ hypernuclei
Λ (39 nuclides), Σ (1)
Z
陽子数
N
中性子数
1
0
Λ
p
n

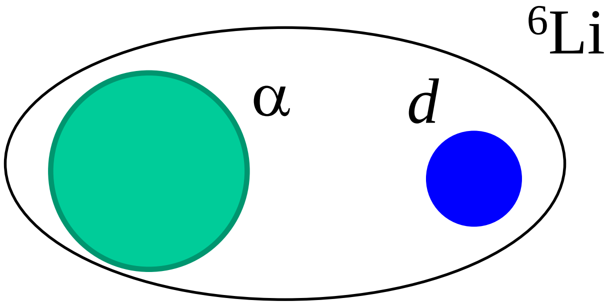

Strangeness
neutron star
ΛΛ, Ξ hypernuclei
ΛΛ (3nuclides)
Λ, Σ hypernuclei
Λ (39 nuclides), Σ (1)
Λ
p
n
Z
陽子数
N
中性子数
2
1
0

Introduction

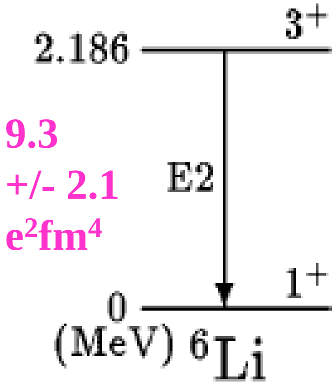
Impurity effects: one of the main interests of hypernuclear physics

how does a Λ particle 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



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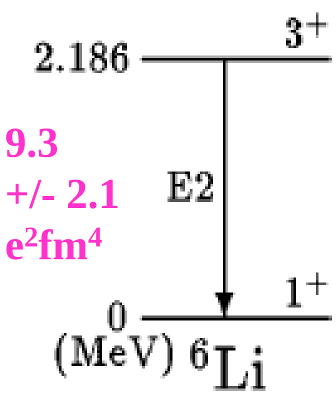

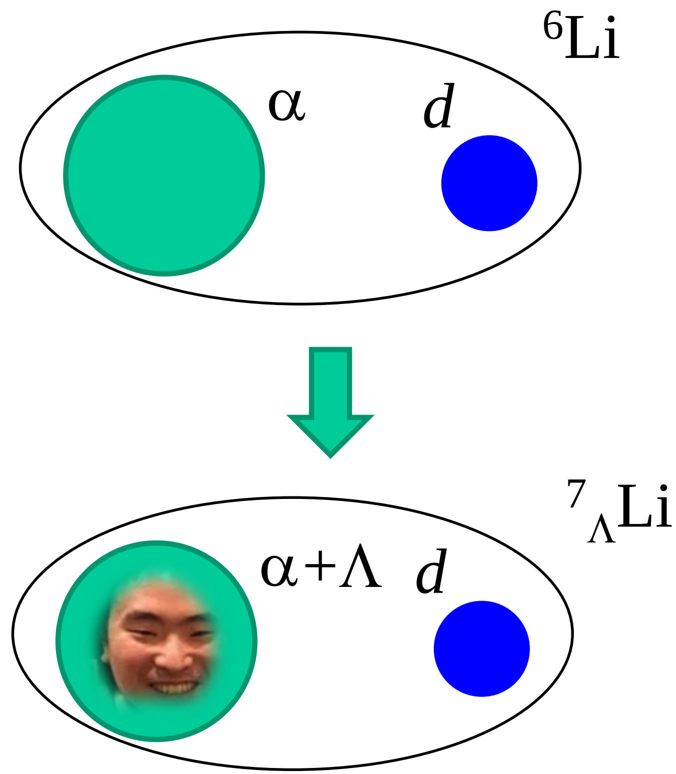

K. Tanida et al., PRL86 ('01) 1982

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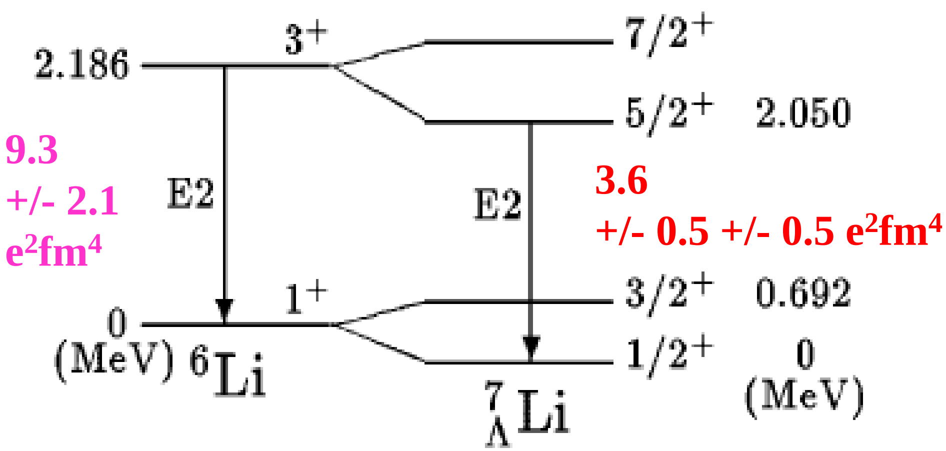
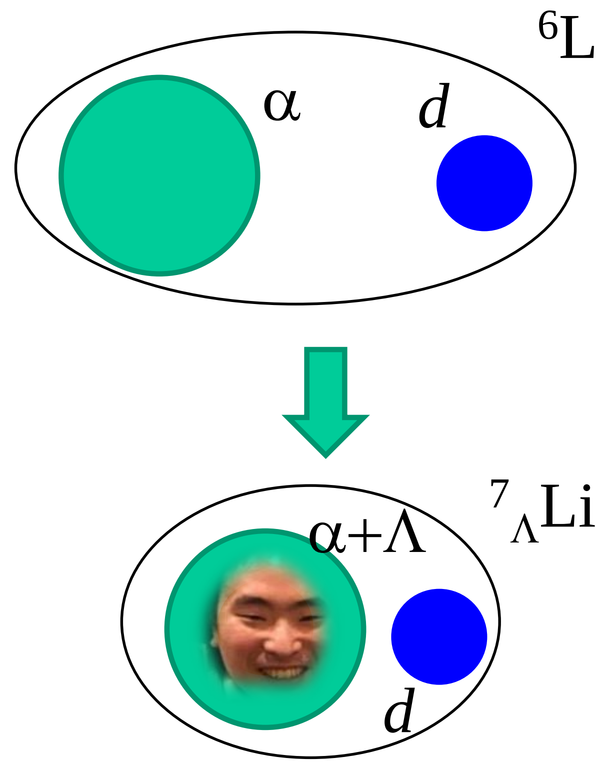


K. Tanida et al., PRL86 (‘01) 1982



about 19% reduction of size
(shrinkage effect)

Introduction

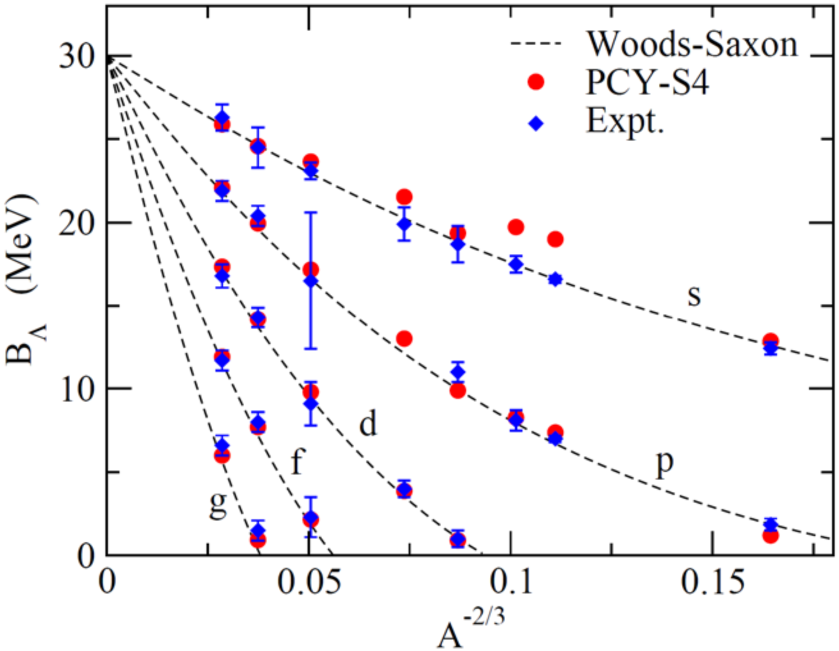
Impurity effects: one of the main interests of hypernuclear physics

how does a Λ particle affect several properties of atomic nuclei?

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

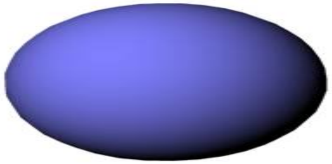
Theoretical approaches:

- ✓ cluster model
- ✓ shell model
- ✓ AMD
- ✓ self-consistent mean-field models



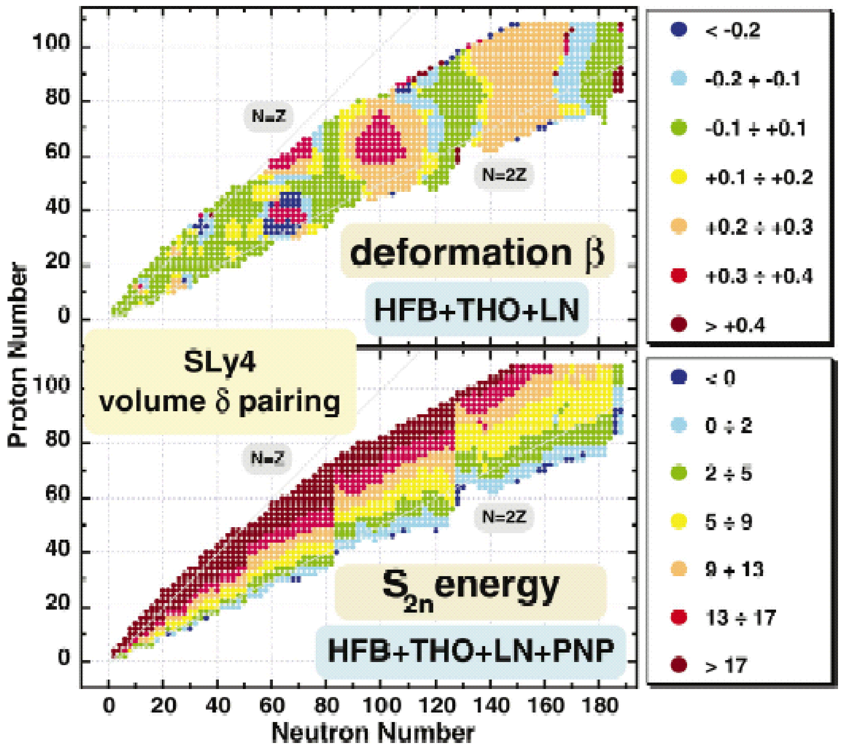
K.H. and J.M. Yao,
Int. Rev. Nucl. Phys. 10 ('16) 263

Mean-field approximation and beyond

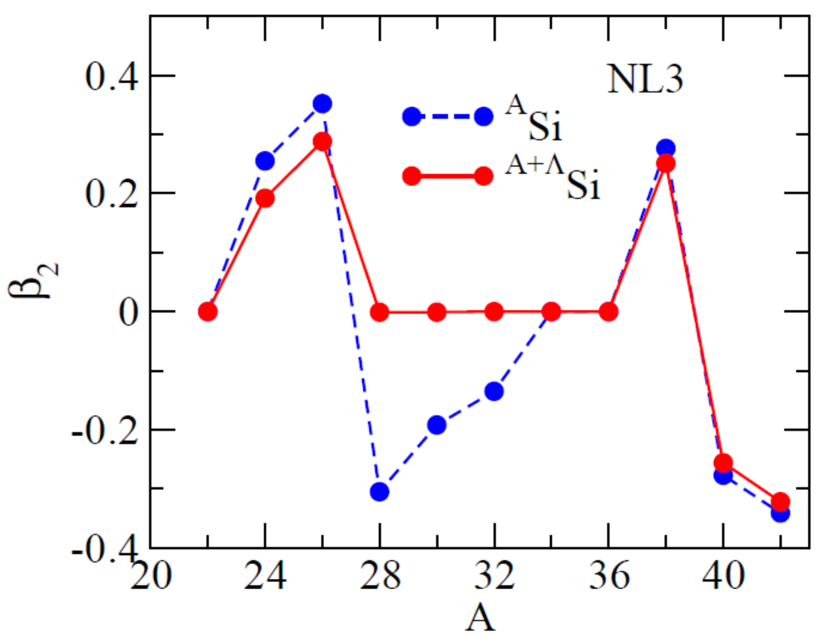


Self-consistent mean-field (Hartree-Fock) method:

- independent particles in a mean-field potential
- global theory for **the whole nuclear chart**
- body-fixed frame → intuitive picture for nuclear deformation
- optimized shape can be automatically determined

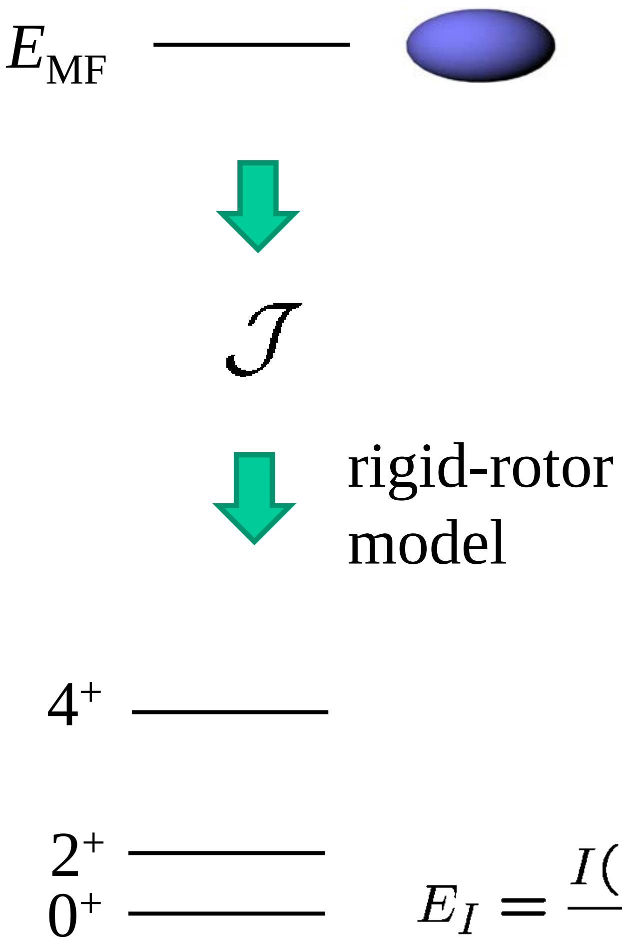


M.V. Stoitsov et al., PRC68('03)054312

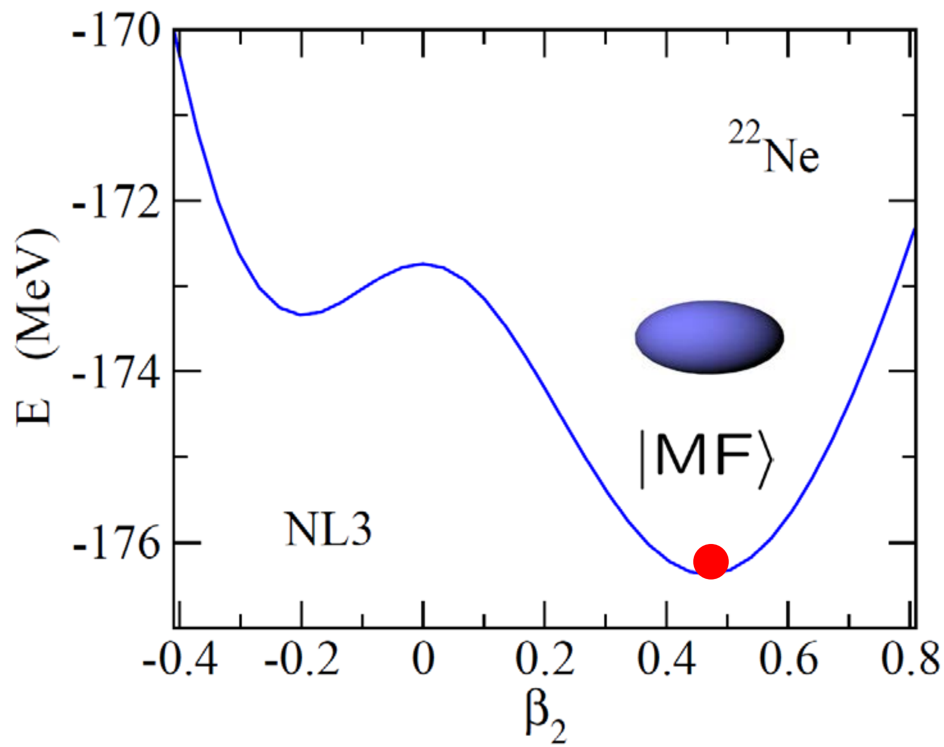


Myaing Thi Win and K.H.,
PRC78('08)054311

spectrum based on the mean-field approximation?



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



spectrum based on the mean-field approximation?

angular mom. projection

4^+ —— $\hat{P}_{I=4}|\mathrm{MF}\rangle$

E_{MF} —— $|\mathrm{MF}\rangle$

2^+ —— $\hat{P}_{I=2}|\mathrm{MF}\rangle$

0^+ —— $\hat{P}_{I=0}|\mathrm{MF}\rangle$

⇩

$\mathcal{J}$

⇩ rigid-rotor model

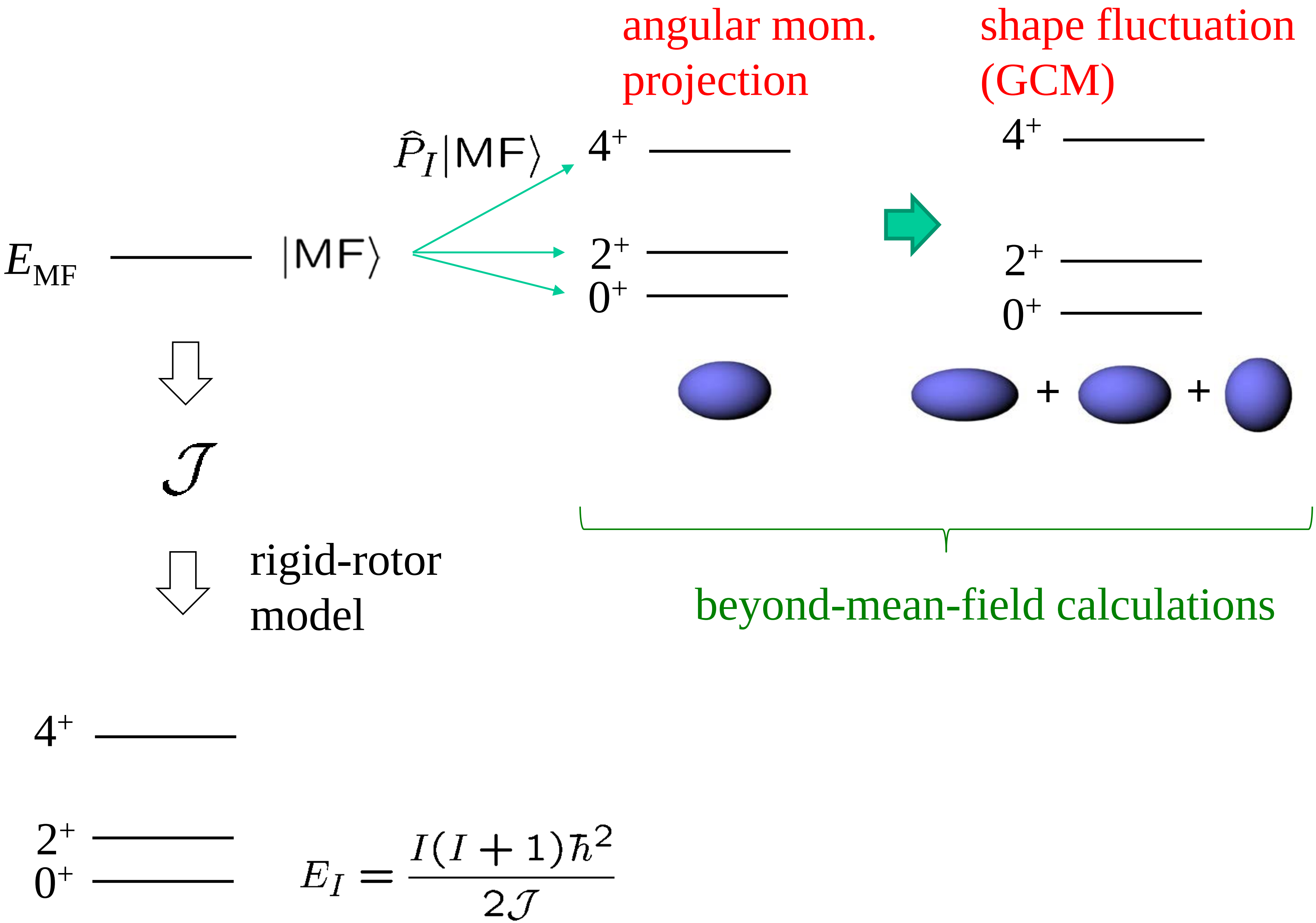
4^+ ——

2^+ ——

0^+ ——

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

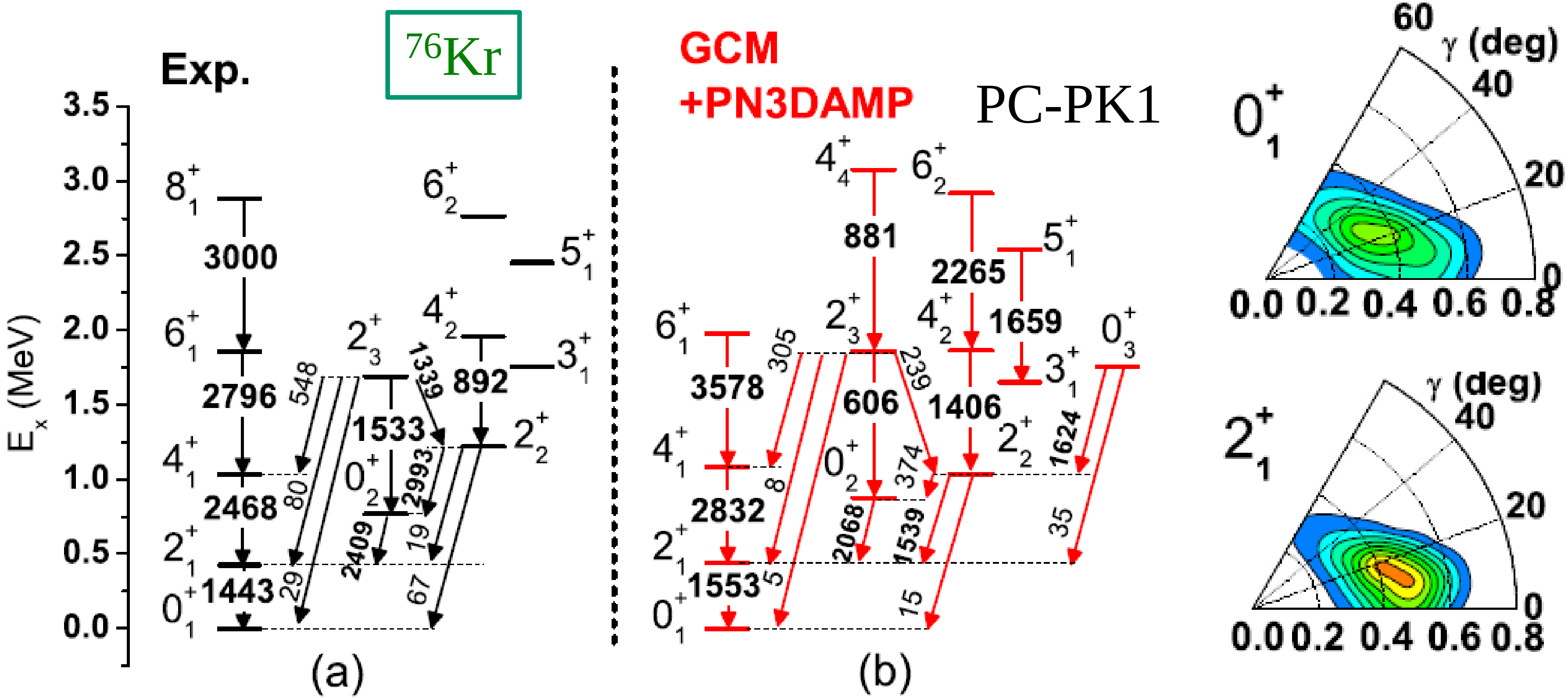
spectrum based on the mean-field approximation?



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

beyond mean-field calculations

- ✓ angular momentum + particle number projections
- ✓ quantum fluctuation (GCM)



J.M. Yao, K.H., Z.P. Li, J. Meng, and P. Ring, PRC89 ('14) 054306

cf. collective coordinates: Quadrupole moments (local operators)

Beyond Mean-Field calculations for hypernuclei

◆ Projection+GCM for the whole（A_c+1） system

H. Mei, K.H. and J.M. Yao, PRC93 (‘16) 011301(R)

$$|\Psi_{IM}\rangle = \int d\beta f(\beta)\, \hat{P}^I_{MK} \hat{P}^N \hat{P}^Z \left[|\Psi_{\mathrm{A_c}}(\beta)\rangle |\Psi_\Lambda(\beta)\rangle \right]$$

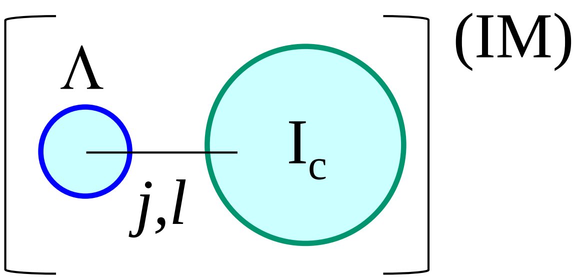
cf. Hill-Wheeler eq. for each *I*

◆ Microscopic particle-rotor model for single-Λ hypernuclei

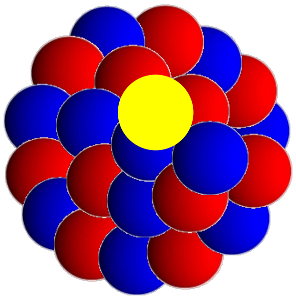
H. Mei, K.H., J.M. Yao, and T. Motoba,

- ✓ PRC90 (‘14) 064302
- ✓ PRC91 (‘15) 064305
- ✓ PRC93 (‘16) 044307
- ✓ PRC96 (‘17) 014308
- ✓ arXiv: 1804.06558.

$$|\Psi_{IM}\rangle = \sum_{j,l,I_c}$$



Microscopic particle-rotor model for hypernuclei



hypernucleus: a clear separation of deg. of freedom

→ Λ+core model

$$|\mathrm{g.s.}\rangle \sim \psi_{s_{1/2}}(\Lambda) \otimes \Psi_{\mathrm{core}}(0^+) + \psi_{d_{5/2}}(\Lambda) \otimes \Psi_{\mathrm{core}}(2^+) + \cdots$$

Λ+core model with core excitations

4^+ ——

2^+ ——

0^+ ——

core nucleus

⇐ beyond MF (proj.+GCM) calculations

- ✓ fully microscopic
- ✓ shape fluctuation
  cf. conventional part.-rot model
- ✓ no Pauli principle
- ✓ rot. and vib. on the equal footing
- ✓ transitional core

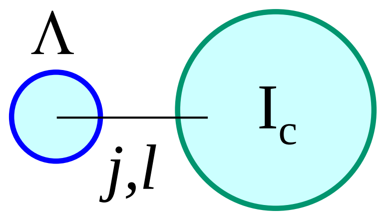
◆ Microscopic particle-rotor model for single-Λ hypernuclei

H. Mei, K.H., J.M. Yao, and T. Motoba, PRC90('14)064302, PRC91('15) 064305
PRC93('16)044307, PRC96('17) 014308

i) beyond mean-field calculations for e-e core: $|\Phi_{0^+}\rangle, |\Phi_{2^+}\rangle, |\Phi_{4^+}\rangle, \cdots$

ii) coupling of Λ to the core states

$$|\Phi_{IM}\rangle = \sum_{j,l,I_c} \left[\quad \right]^{(IM)}$$



Λ+core model with core excitations

$$\Psi_{JM}(\boldsymbol{r}_\Lambda, \{\boldsymbol{r}_i\}) = \sum_{n,j,\ell,I} R_{j\ell nI}(r_\Lambda)[\mathcal{Y}_{j\ell}(\hat{\boldsymbol{r}}_\Lambda) \otimes \Phi_{nI}(\{\boldsymbol{r}_i\})]^{(JM)}$$

$$H = H_c + T_\Lambda + \sum_{i=1}^{A_c} v_{N\Lambda}(\boldsymbol{r}_\Lambda, \boldsymbol{r}_i)$$

⇒ coupled equations for R_{jlnI}

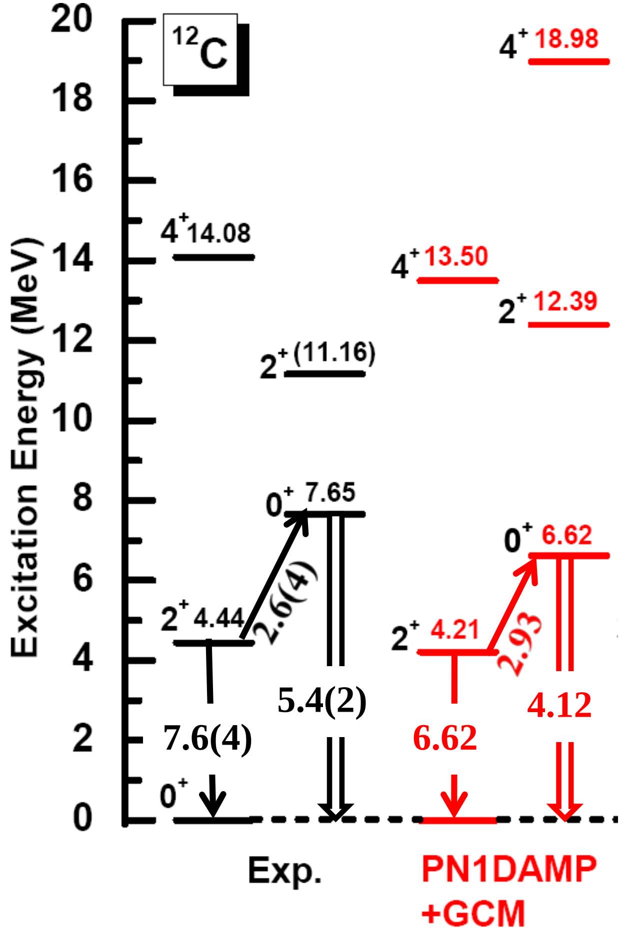
$v_{N\Lambda}$: point coupling relativistic NΛ interaction

Microscopic Particle-Rotor Model for Λ hypernuclei

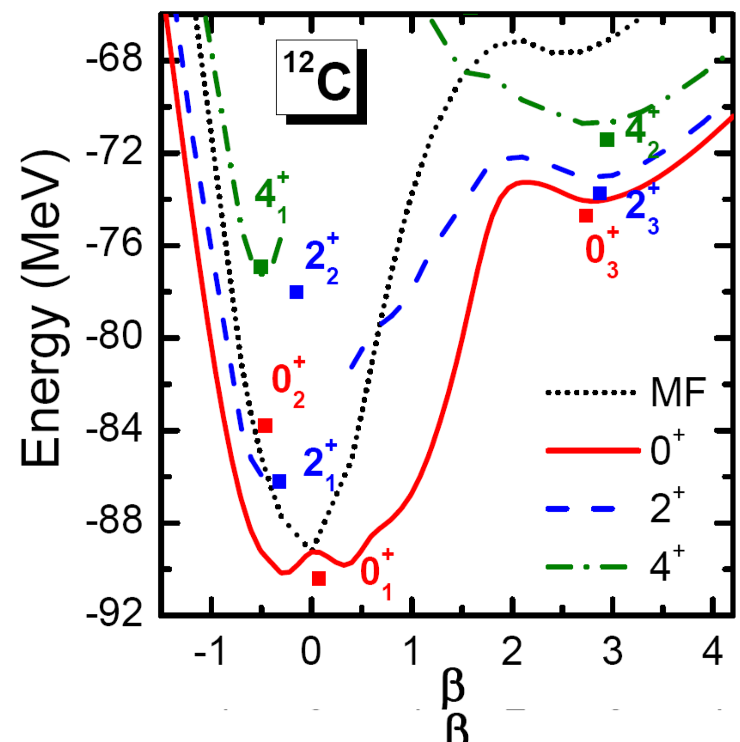
Example: $^{13}{}_{\Lambda}C$

i) beyond mean-field calculations for e-e core (^{12}C) : GCM + projections

$$|\Phi_{I_cM_c}\rangle = \int d\beta\, f(\beta)|\Psi_{I_cM_c}(\beta)\rangle = \int d\beta\, f(\beta)\hat{P}^{I_c}_{M_cK_c}\hat{P}^N\hat{P}^Z|\Psi_{\mathrm{MF}}(\beta)\rangle$$



✓ axial symmetry
✓ relativistic PC-F1



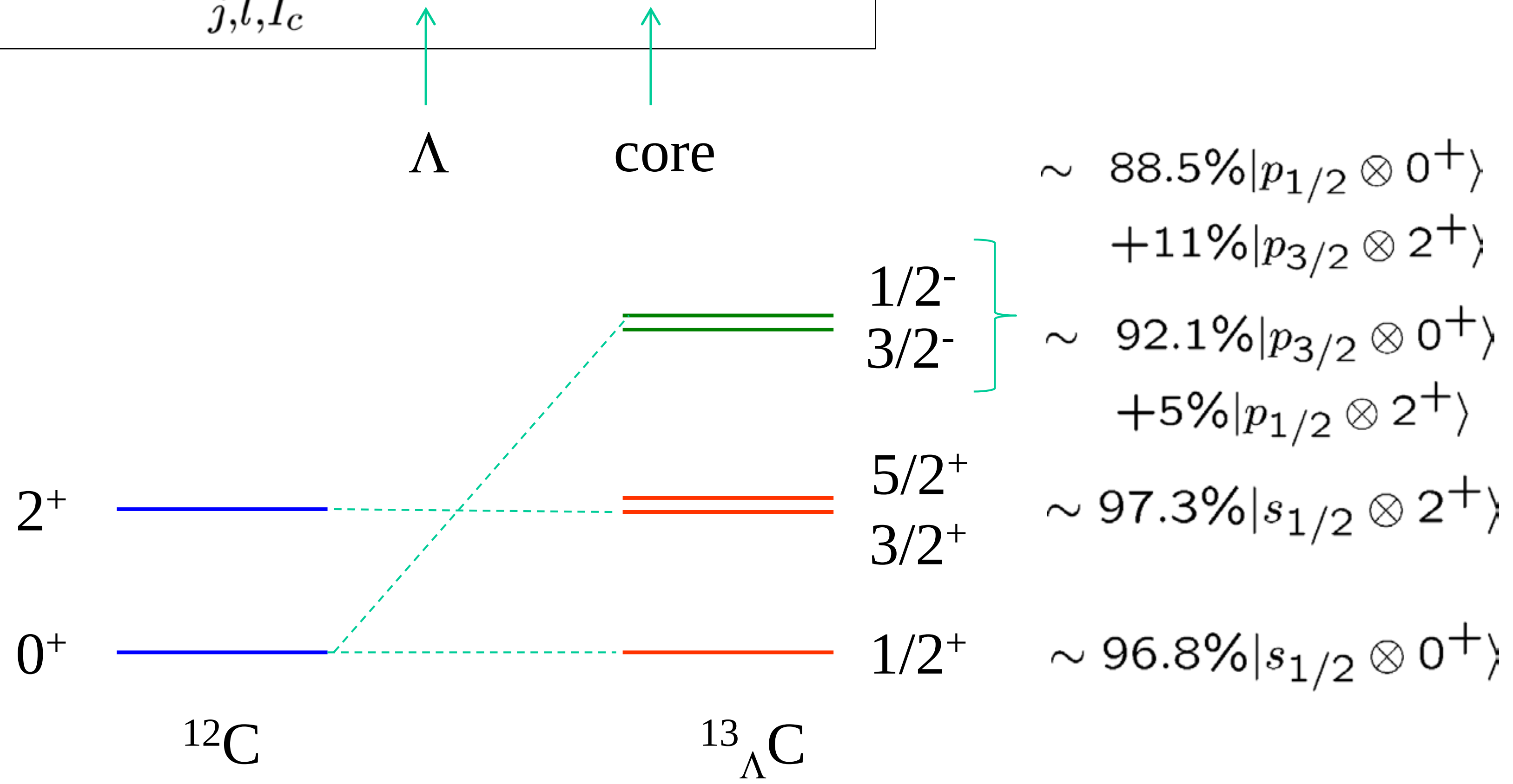
Microscopic Particle-Rotor Model for Λ hypernuclei

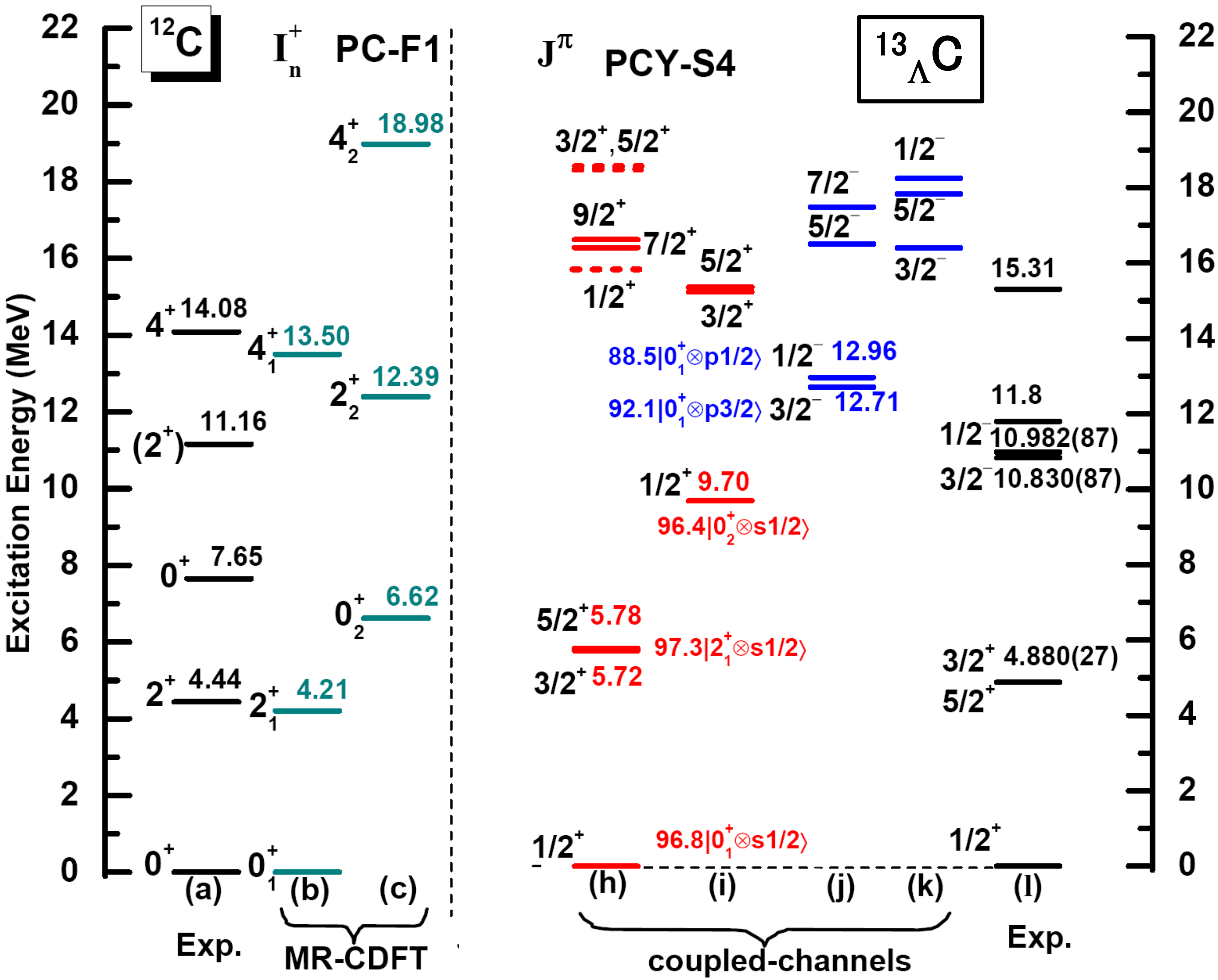
Example: $^{13}_{\Lambda}C$

(i) beyond mean-field calculations for e-e core (^{12}C)

(ii) coupling of Λ to the core states

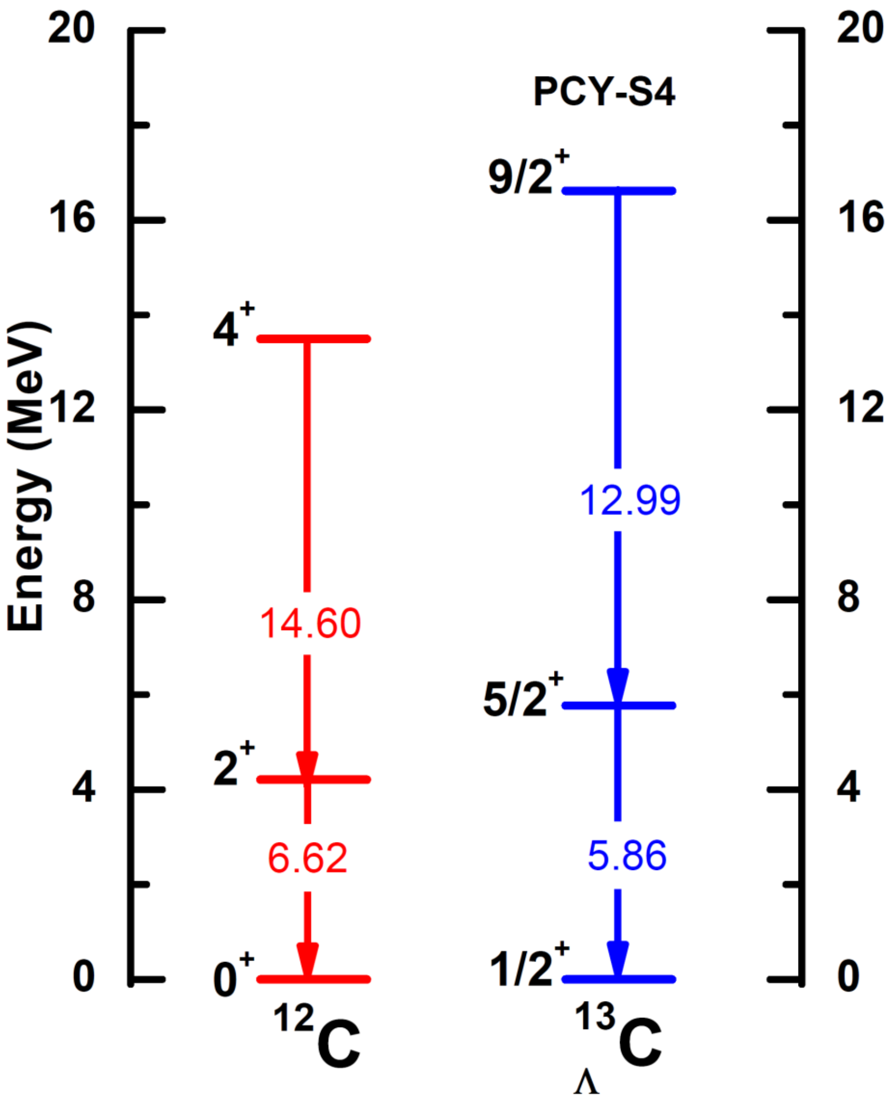
$$|\Phi_{IM}\rangle = \sum_{j,l,I_c} \left[\psi_{jl}(\boldsymbol{r}_\Lambda) \otimes |\Phi_{I_c}\rangle\right]^{(IM)}$$

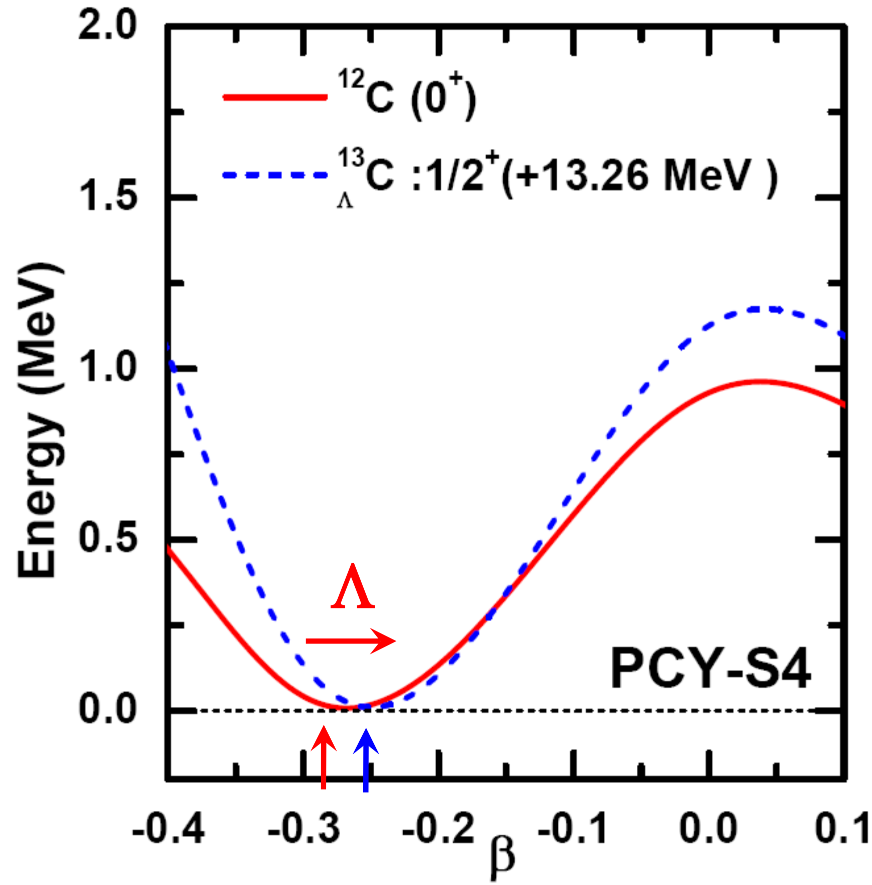




H. Mei, K.H., J.M. Yao, T. Motoba, PRC93 ('16) 044307

B(E2) transition rates (e^2fm^4)



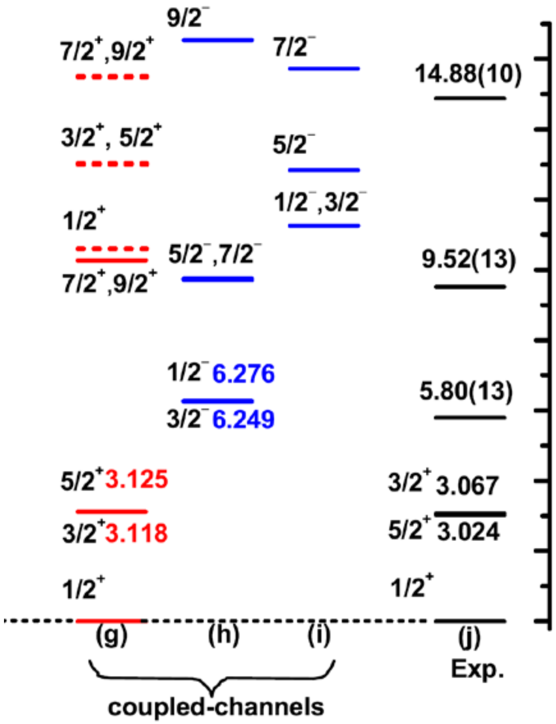


	^{12}C	$^{13}_{\Lambda}C$
β	-0.27	-0.25
r_p (fm)	2.44	2.39

- B(E2) : ~ 11% reduction

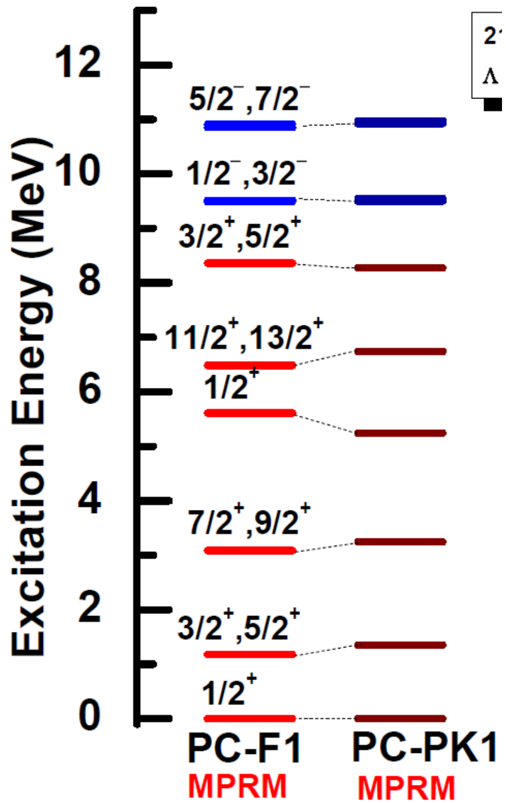
other applications:

$^{9}_{\Lambda}$Be

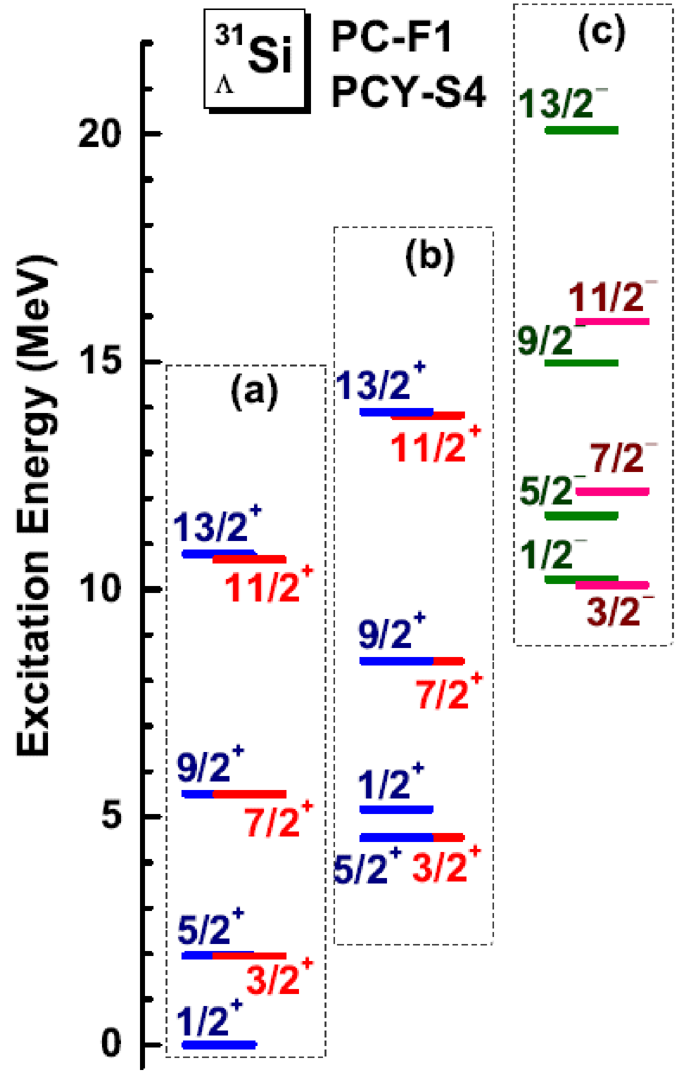


H. Mei, K.H., J.M. Yao, T. Motoba, PRC90 (‘14) 064302

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

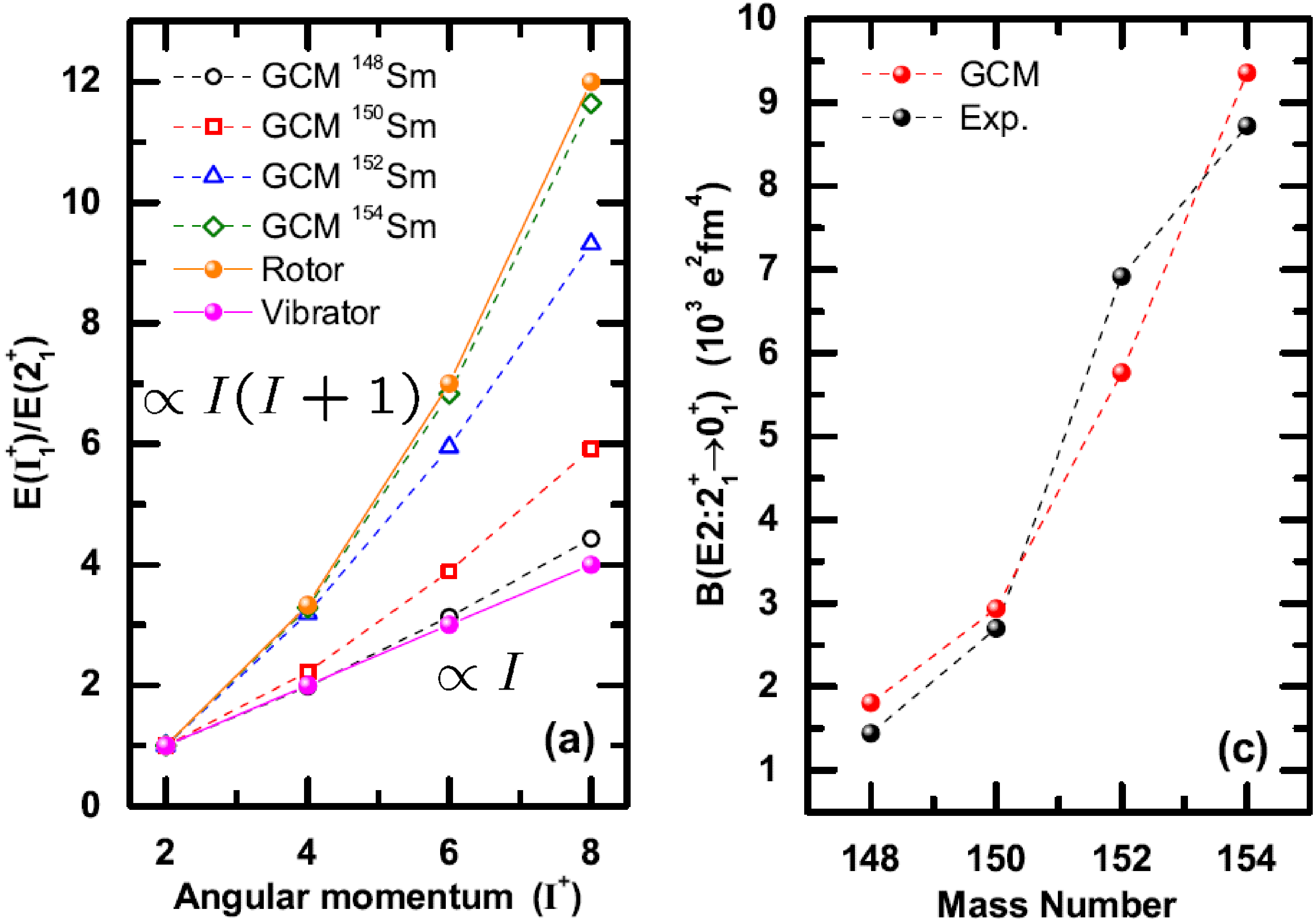


H. Mei, K.H., J.M. Yao, T. Motoba, PRC91 (‘15) 064305



H. Mei, K.H., J.M. Yao, T. Motoba, arXiv: 1804.06558.

Application to Sm isotopes



Results for $^{155}_{\Lambda}Sm$

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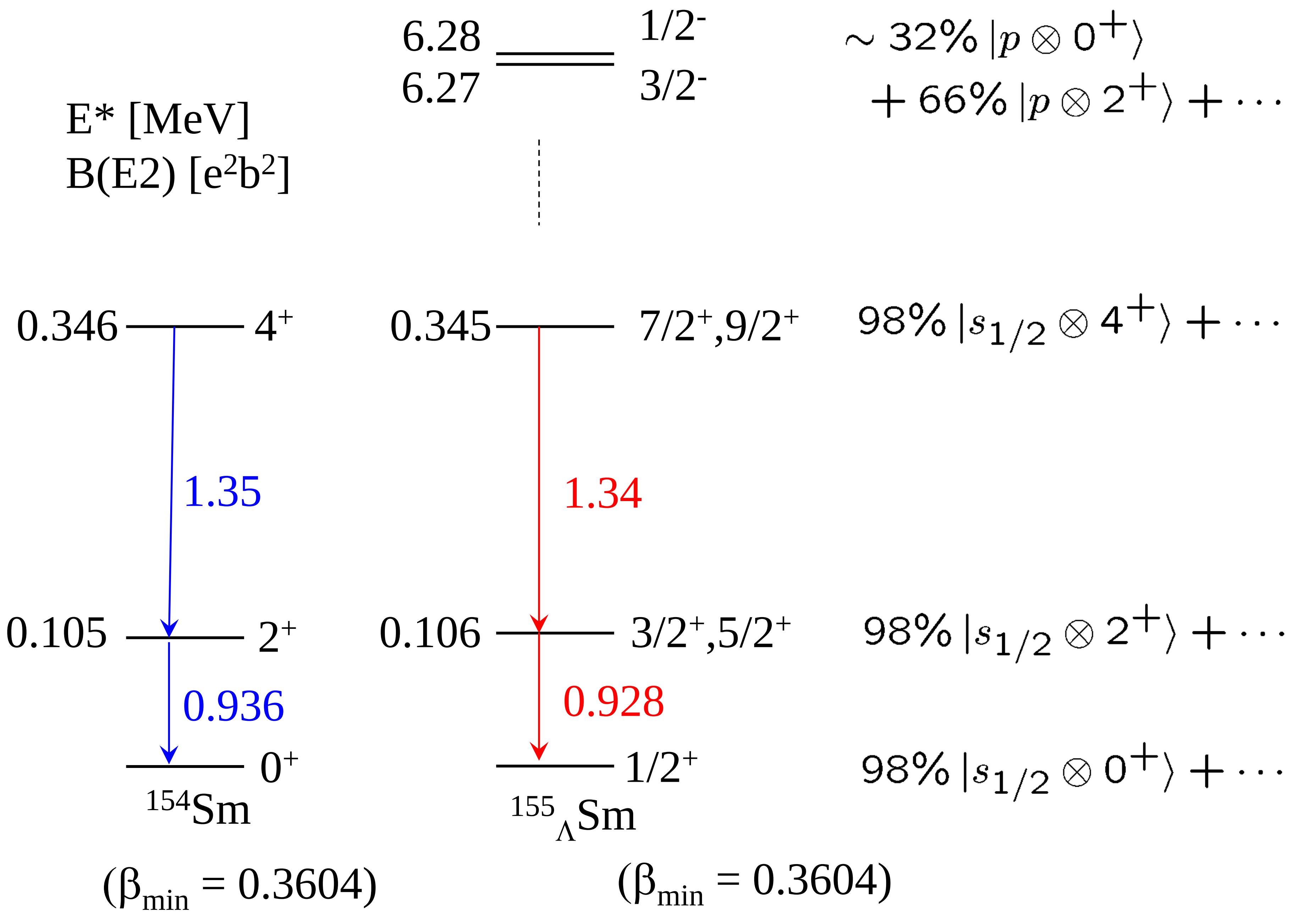
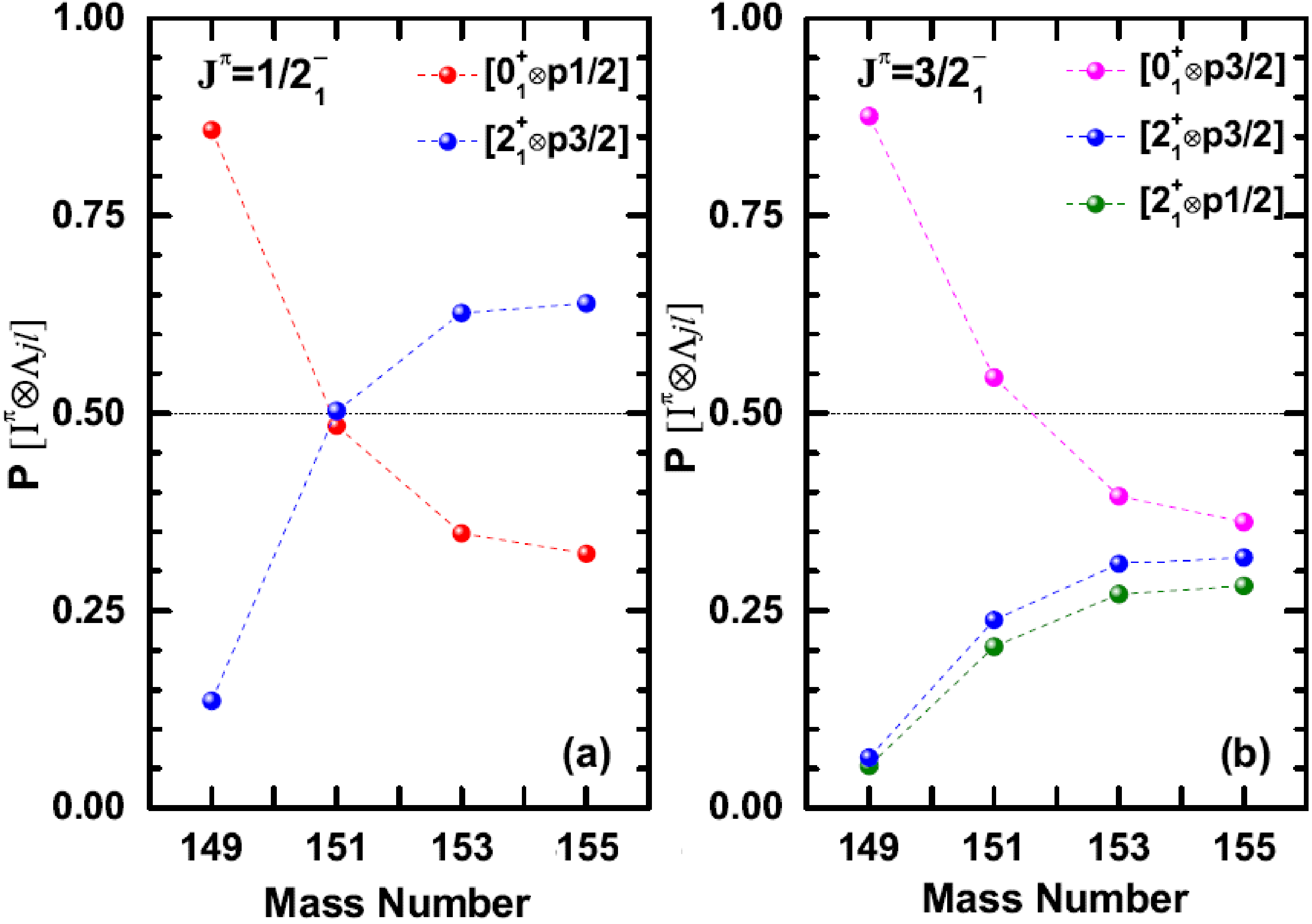


weak coupling → strong coupling



H. Mei, K.H., J.M. Yao, and T. Motoba,
PRC96 (‘17) 014308

Summary

Applications of Beyond-Mean-Field method to hypernuclei

- Low-lying spectra of Λ hypernuclei

  Microscopic particle-rotor/vibrator model

  ✓ Λ + GCM states for core: particle-core model with core excitations
  ✓ the first calculations for low-lying spectra for hypernuclei based on mean-field type calculations
  ✓ from C to Sm: both rotor and vibrator on an equal footing
  ✓ transitional nuclei

- Future perspectives

  ✓ extension to include triaxiality (cf. $^{25}{}_{\Lambda}$Mg)