Octupole phonon excitations on the shell-model states in Xe, Cs, and Ba isotopes up to mass 142

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Outline of talk

1. Introduction

- Previous systematic shell-model studies
- 50≦Z, 82 ≦ N (North-East) region around ^{132}Sn (This work)
  Octupole-phonon states appear at low energy

2. SM framework

- Shell model framework

3. SM results

- Energy levels, *E2* ratios, *EM* moments

4. Octupole-phonon model

- phenomenologically treat octupole vibrational states

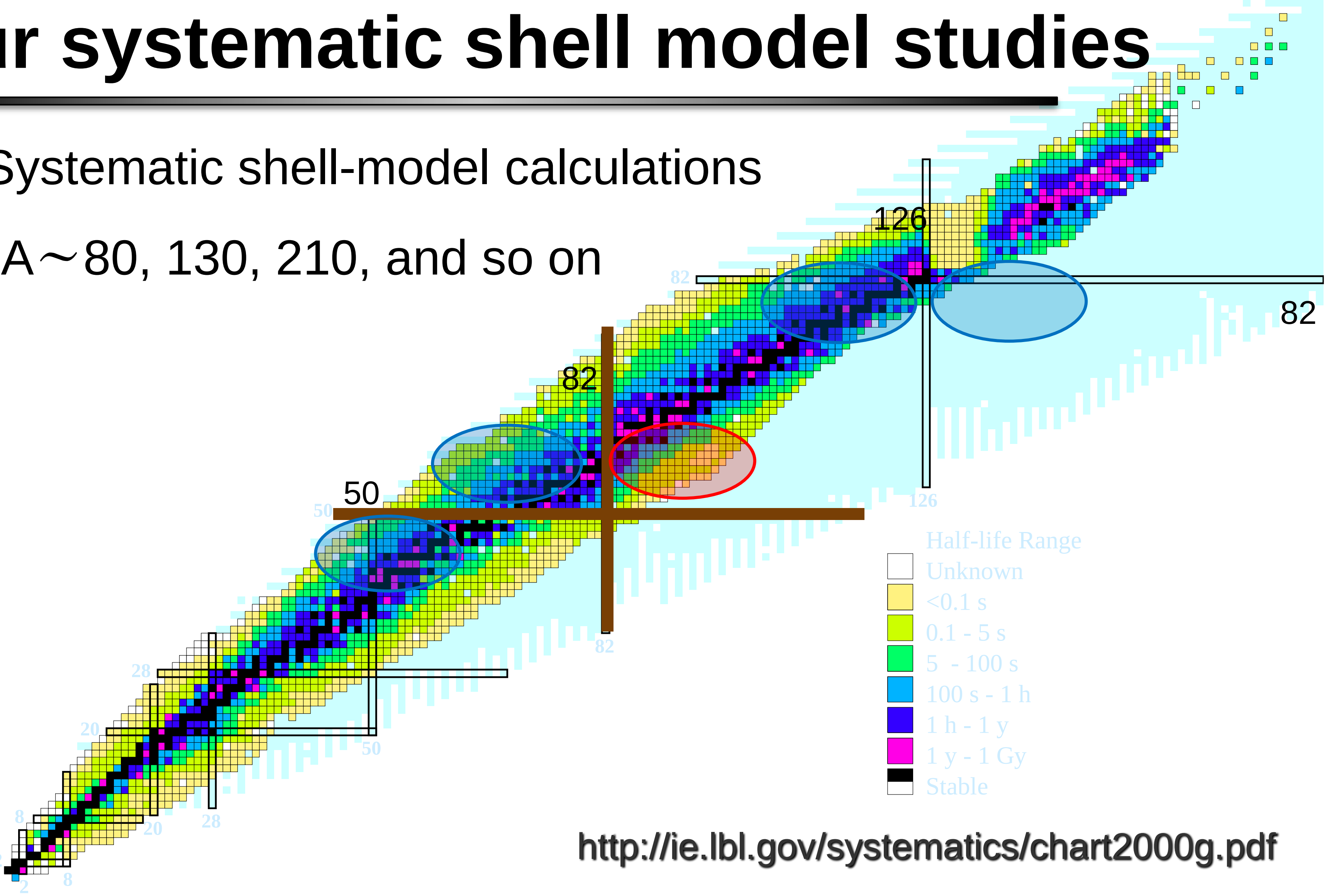
5. Summary

Introduction

Our systematic shell model studies

- Systematic shell-model calculations

A～80, 130, 210, and so on



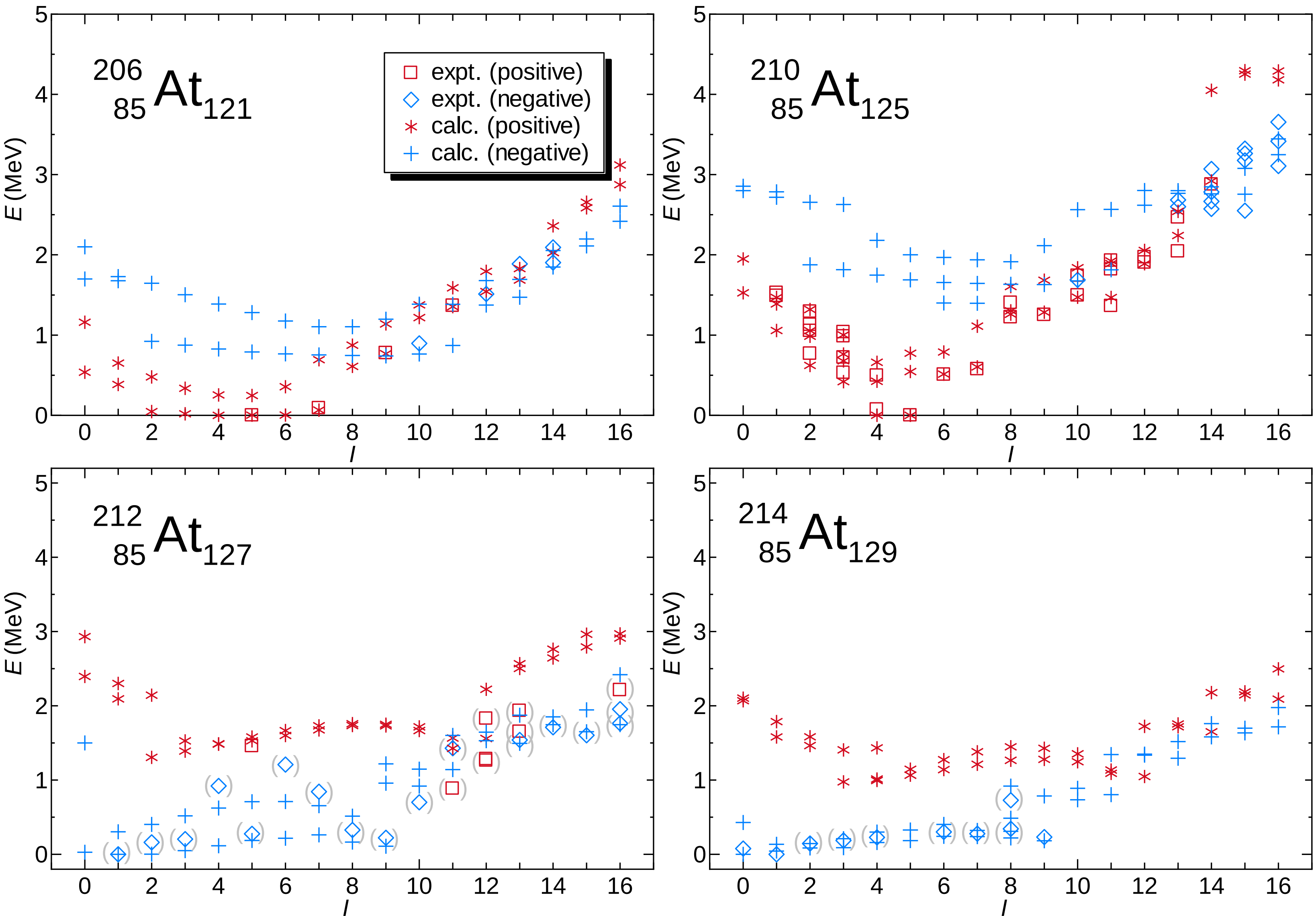
http://ie.lbl.gov/systematics/chart2000g.pdf

At isotope (doubly-odd)

SM study
Previous work

N≦126

N>126



Present work

N≧82

This work

^{133}La	^{134}La	^{135}La	^{136}La	^{137}La	^{138}La	^{139}La				^{143}La	^{144}La
^{132}Ba	^{133}Ba	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba				^{142}Ba	^{143}Ba
^{131}Cs	^{132}Cs	^{133}Cs	^{134}Cs	^{135}Cs	^{136}Cs	^{137}Cs	^{138}Cs	^{139}Cs	^{140}Cs	^{141}Cs	^{142}Cs
^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe	^{138}Xe	^{139}Xe	^{140}Xe	^{141}Xe
^{129}I	^{130}I	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{136}I	^{137}I	^{138}I	^{139}I	^{140}I
^{128}Te	^{129}Te	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te
^{127}Sb	^{128}Sb	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb
^{126}Sn	^{127}Sn	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn
^{125}In	^{126}In	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In				^{135}In	^{136}In

$N = 82$

Various nuclear structures in ^{140}Xe studied by β decay of ground and isomeric states in ^{140}I

A. Yagi,[1,2] A. Odahara,[1,*] H. Nishibata,[1,2,3] R. Lozeva,[4,5] C.-B. Moon,[6,7] S. Nishimura,[2] K. Yoshida,[8] N. Yoshinaga,[9]

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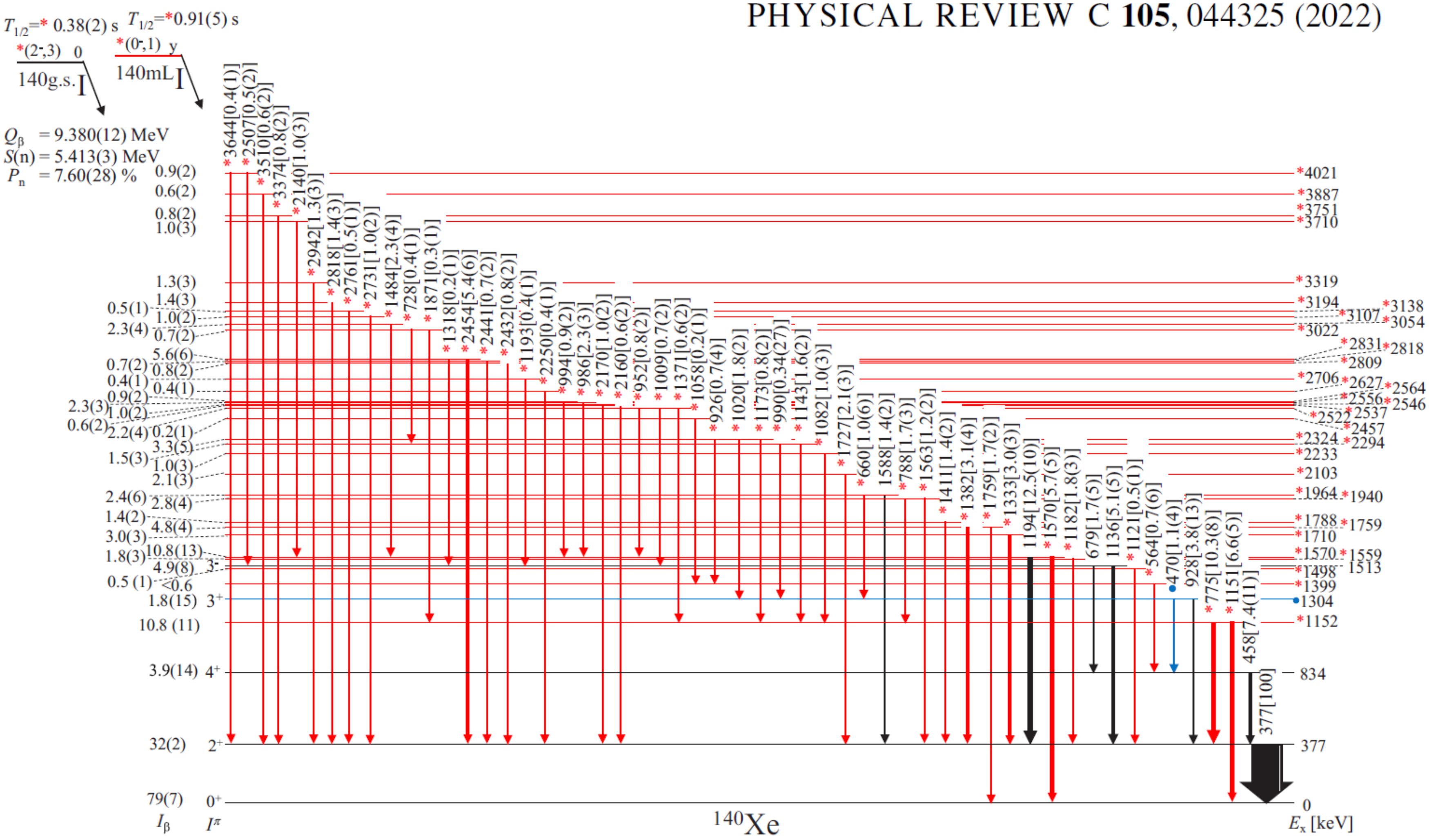
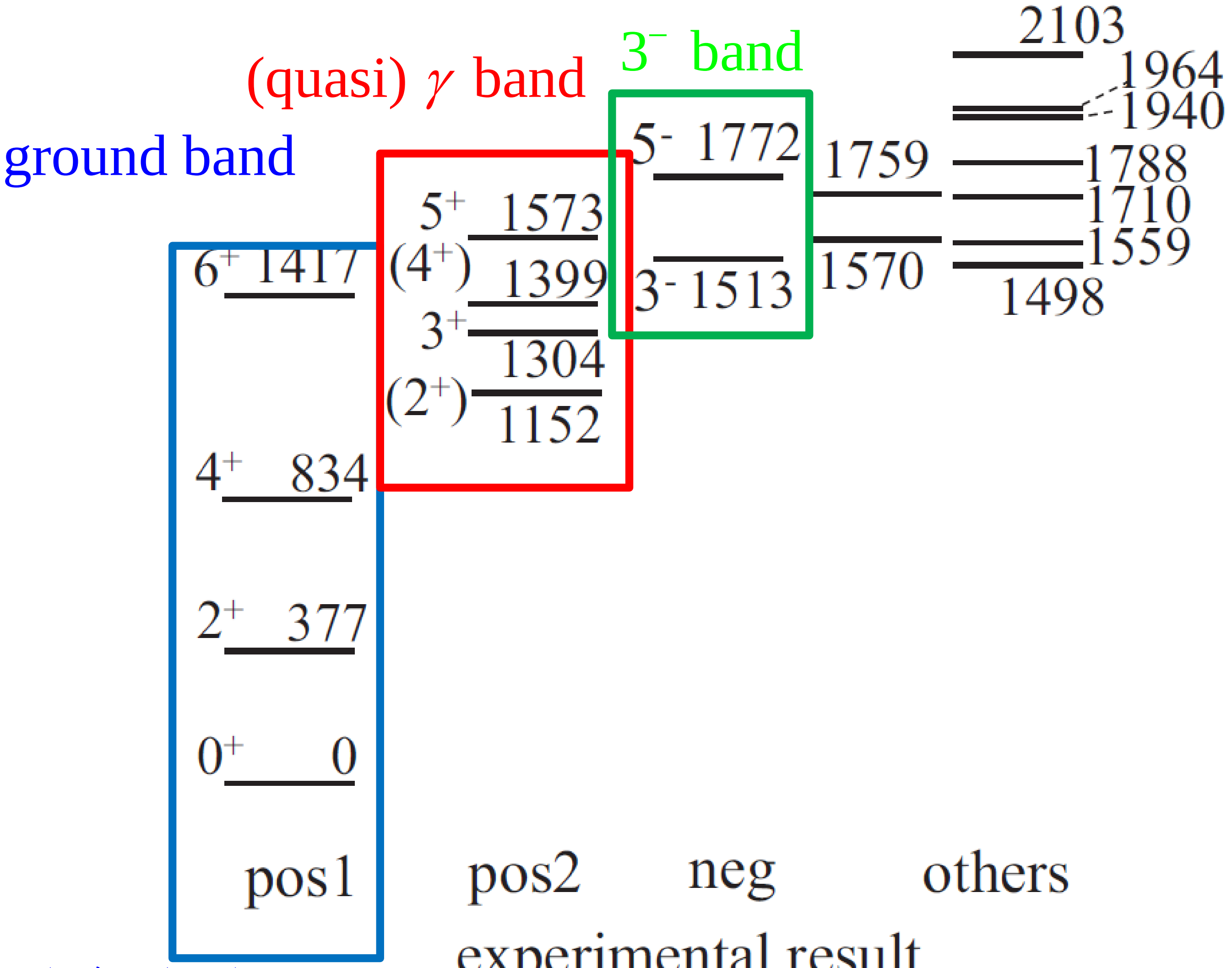


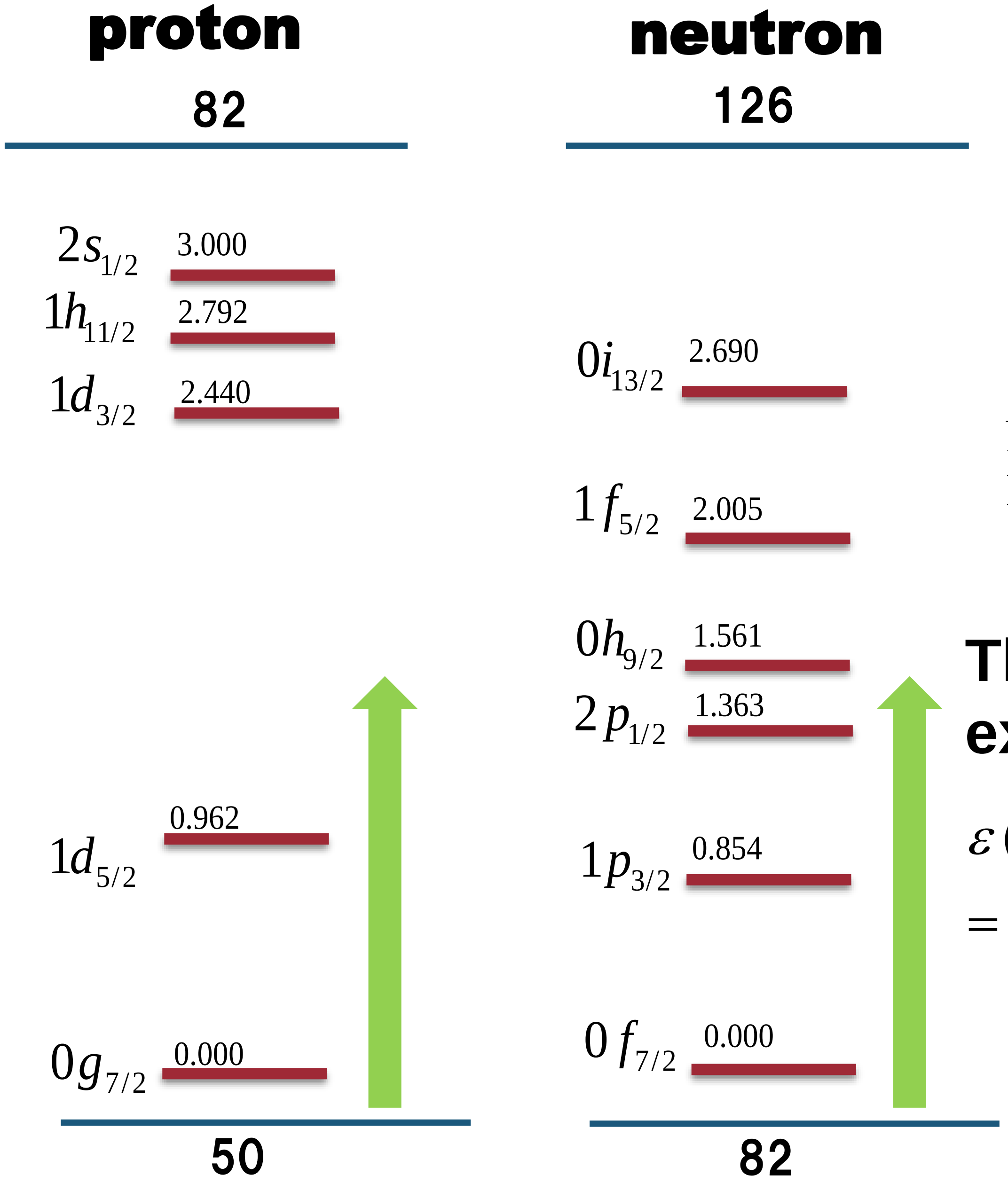
Low-lying band structures in ^{140}Xe



experimental result

$$E\left(4_1^+\right)/E\left(2_1^+\right) = 2.2$$

Framework



proton

82

$2s_{1/2}$ 3.000

$1h_{11/2}$ 2.792

$1d_{3/2}$ 2.440

$1d_{5/2}$ 0.962

$0g_{7/2}$ 0.000

50

neutron

126

$0i_{13/2}$ 2.690

$1f_{5/2}$ 2.005

$0h_{9/2}$ 1.561

$2p_{1/2}$ 1.363

$1p_{3/2}$ 0.854

$0f_{7/2}$ 0.000

82

Single-particle energies (MeV)

N. Yoshinaga et al,.
PRC **109**, 064313 (2024)

They are fixed constant except for $i_{13/2}$ orbit

$$\varepsilon(i_{13/2}) = 2.69 - 0.19N_\pi - 0.19(N_\nu - 1)$$

MeV

Phenomenological Two-body interactions

- Multipole-pairing + *QQ int. for like nucleons*

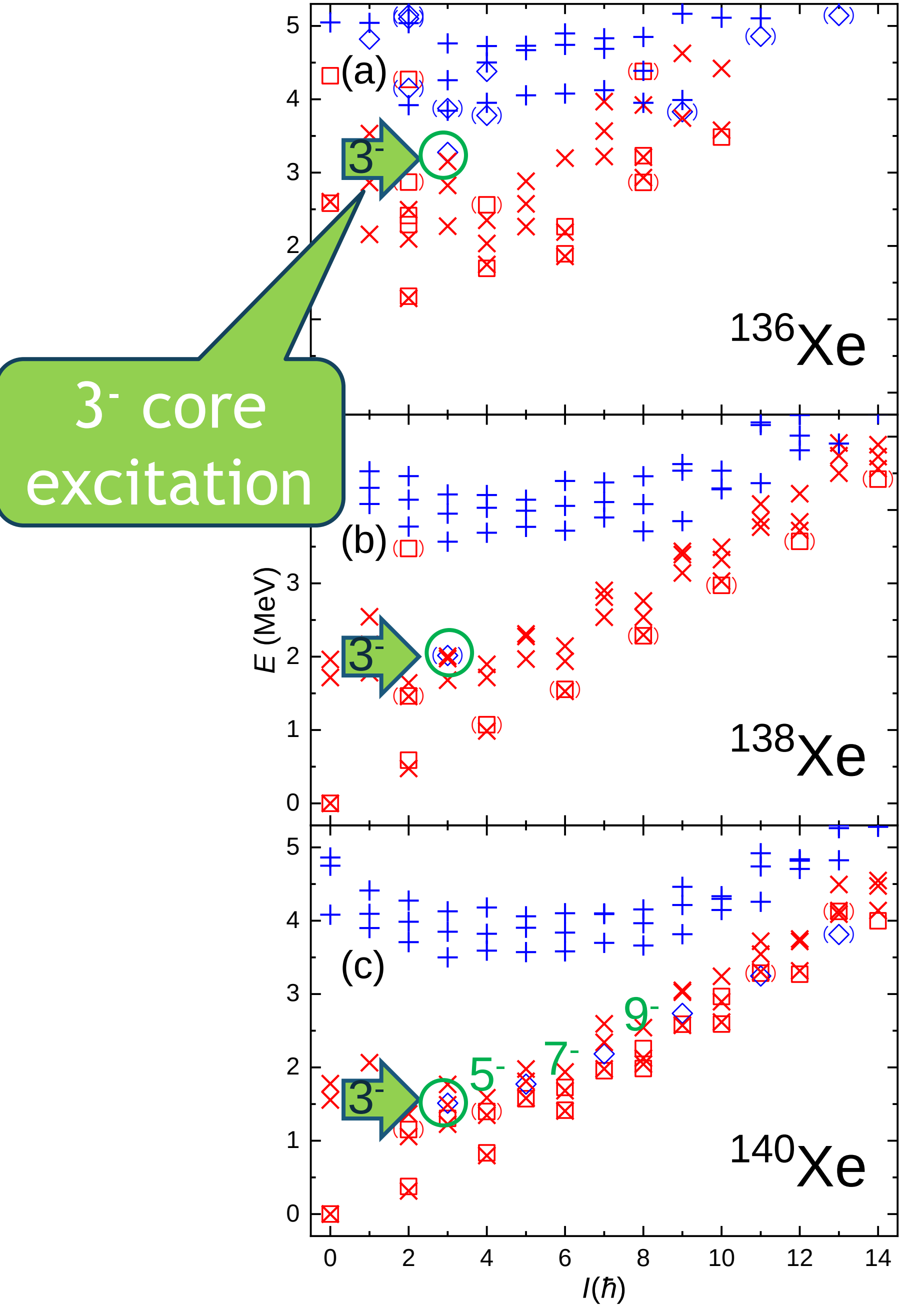
- Only *QQ* int. between neutrons and protons

They are determined in two-body systems

Strengths are fixed constant for all nuclei

SM results

Xe isotope (even)



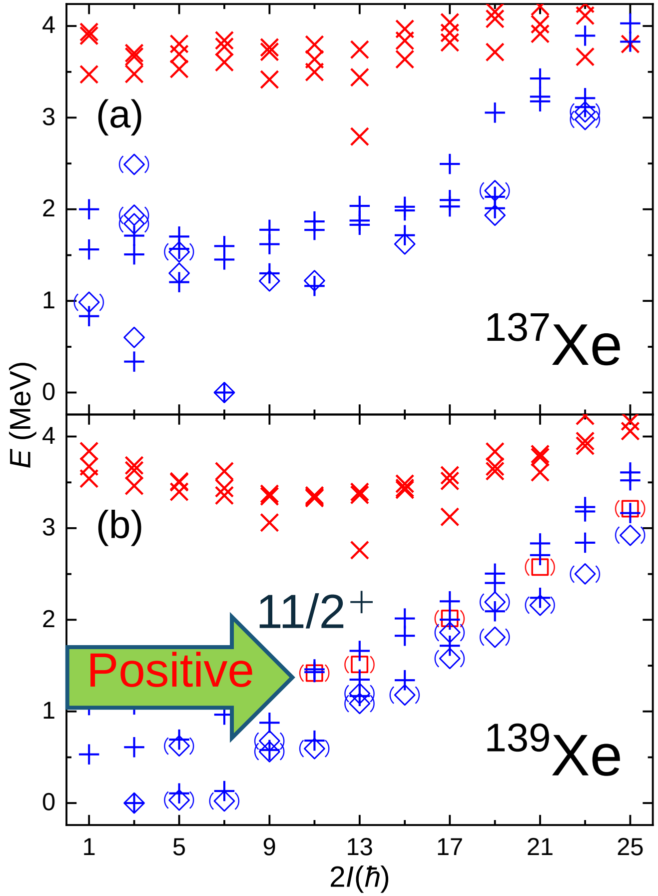
3- core excitation

N. Yoshinaga et al,.PRC **109**, 064313 (2024)

Low-lying states are excellently reproduced except some negative parity states

- □ Expt. (positive)
- ◇ Expt. (negative)
- × Calc. (positive)
- + Calc. (negative)

Xe isotope (odd)



Low-lying states are excellently reproduced except some positive parity states

□ Expt. (positive)
◇ Expt. (negative)
× Calc. (positive)
+ Calc. (negative)

SM results

E2 transition rates; B(E2)

^{136}Xe	expt. [W.u.]	calc. [W.u.]
$2^+ \to 0^+$	9.7 (4)	9.75
$4^+ \to 2^+$	1.281 (17)	2.59
$6^+ \to 4^+$	0.0132 (8)	0.05
$8^+ \to 6^+$	>0.26	0.60

fixed

Effective charge

$$e_\nu = \delta e \qquad e_\pi = (1+\delta)e$$

$$\delta = 0.64$$

^{142}Ba	expt. [W.u.]	calc. [W.u.]
$2^+ \to 0^+$	32.1 (10)	45.0
$4^+ \to 2^+$	45 (4)	64.0
$2^+_2 \to 2^+_1$	>0.48 (5)	0.525
$6^+_1 \to 4^+_1$	18 (4)	68.8

^{139}Cs	expt. [W.u.]	calc. [W.u.]
$5/2^+ \to 7/2^+$	6.3 (4)	5.35
$3/2^+ \to 5/2^-$	26 (23)	10.3
$1/2^+ \to 5/2^+$	37 (1)	76.5

Cf. $6^+_1 \to 4^+_1$: 68.8 , $6^+_2 \to 4^+_1$: 0.494

Magnetic and Quadrupole moments

Magnetic moments

$g_{\ell\nu} = 0.00,\ g_{\ell\pi} = 1.00,\ g_{s\nu} = -2.68,\ g_{s\pi} = 3.91$

^{136}Xe	expt. [μ_N]	calc. [μ_N]
2^+	1.54 (10)	+1.50
4^+	3.2 (6)	+2.86
6^+	5.45 (5)	+5.058
^{137}Xe	**expt. [μ_N]**	**calc. [μ_N]**
$7/2^-$	-0.9704 (10)	−1.13
$15/2^-$	2.0 (4)	+2.17

^{138}Ba	expt. [μ_N]	calc. [μ_N]
2^+	+1.44 (22)	+1.70
4^+	3.2 (6)	+3.06
6^+	+5.88 (12)	+4.28
^{138}Cs	**expt. [μ_N]**	**calc. [μ_N]**
3^-	0.700 (4)	+0.372
6^-	1.713 (9)	+1.10

Quadrupole moments

$e_\nu = -0.85e,\ e_\pi = +1.50e$

^{139}Xe	expt. [eb]	calc .[eb]
$3/2^-$	+0.39 (2)	+0.383

^{140}Ba	expt. [eb]	calc. [eb]
2^+	−0.52 (34)	−0.385

Short summary for the SM calculations

- We have carried out the shell model calculation for nuclei beyond ^{132}Sn (North-East region).

Target nuclei : Even-even, odd-mass, and doubly-odd nuclei for Xe, Cs, Ba isotopes up to mass 142

- Energy levels and electromagnetic properties are calculated.
- We have obtained good agreements with the experimental data except some states related with octupole vibrational states

Octupole phonon model

Extension of the SM with one *octupole phonon*

The model unifies the shell-model and the octupole vibration
by introducing an octupole phonon (*f*-boson; 3⁻ boson)

$$\hat{H} = \hat{H}_{SM} + \hat{H}_{f} + \hat{H}_{SM-f}$$

from experimental data

Octupole phonon excitation energy

$$\hat{H}_{f} = \varepsilon_{f}\, f^{\dagger}\cdot\tilde{f}$$

Simplified dipole-dipole interaction

$$\hat{H}_{SM-f} = \alpha\, \boldsymbol{I}_{SM}\cdot\boldsymbol{L}_{f}$$

$\boldsymbol{I}_{SM}$: Angular momentum operator for SM states

$\boldsymbol{L}_{f}$: *f*-boson angular momentum operator

One octupole-phonon only

Basis states : $\left|\Phi\left(I_k,k,\right),f;J\right\rangle = \left[\left|\Phi_{SM}\left(I_k,k,\right)\right\rangle\otimes\left|f\right\rangle\right]^{(J)}$

$$J = \left|I_k - 3\right|,\ \left|I_k - 3\right| + 1,\ \ldots,\ I_k + 3$$

Energies of the states including *f*-boson

Energies

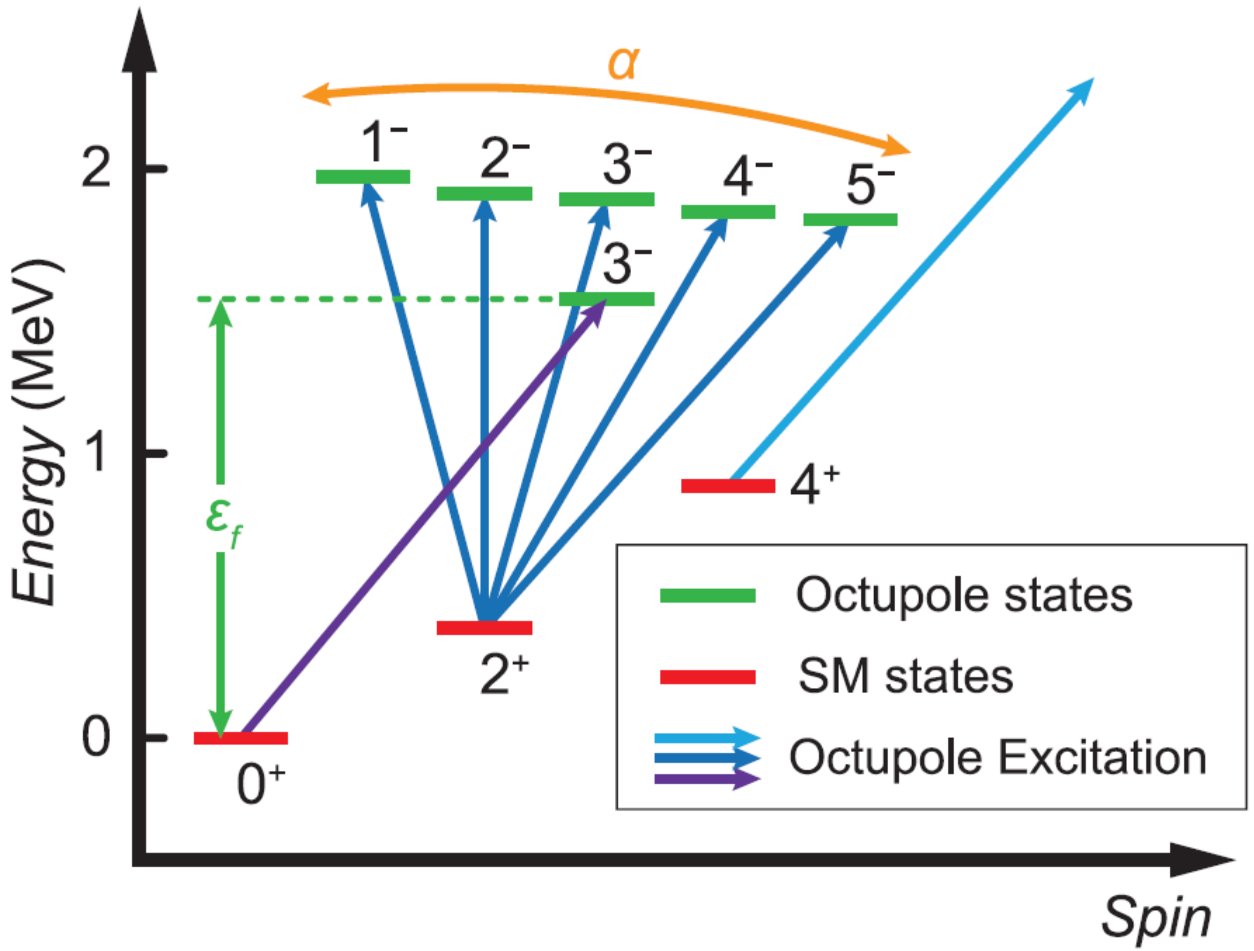
$$E(J)=E_{SM}(I_k,k)+\varepsilon_f+\frac{1}{2}\alpha\left[J(J+1)-I_k(I_k+1)-12\right]$$

Two parameters

ε_f Determined by experimental data (3- excitation energy)

$$\alpha=-0.01\ \mathrm{MeV}$$

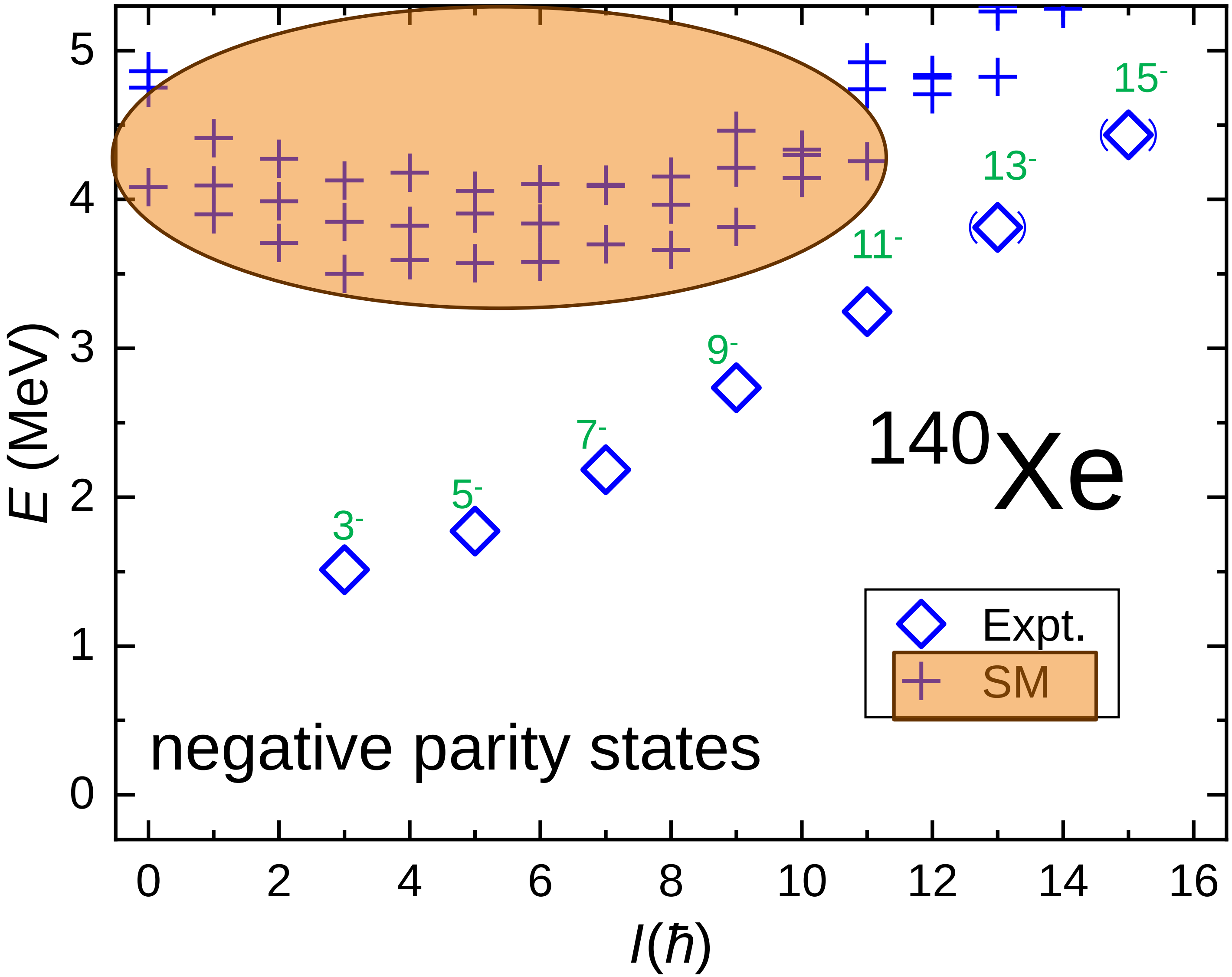
Octupole-phonon states on SM states



Schematic Diagram

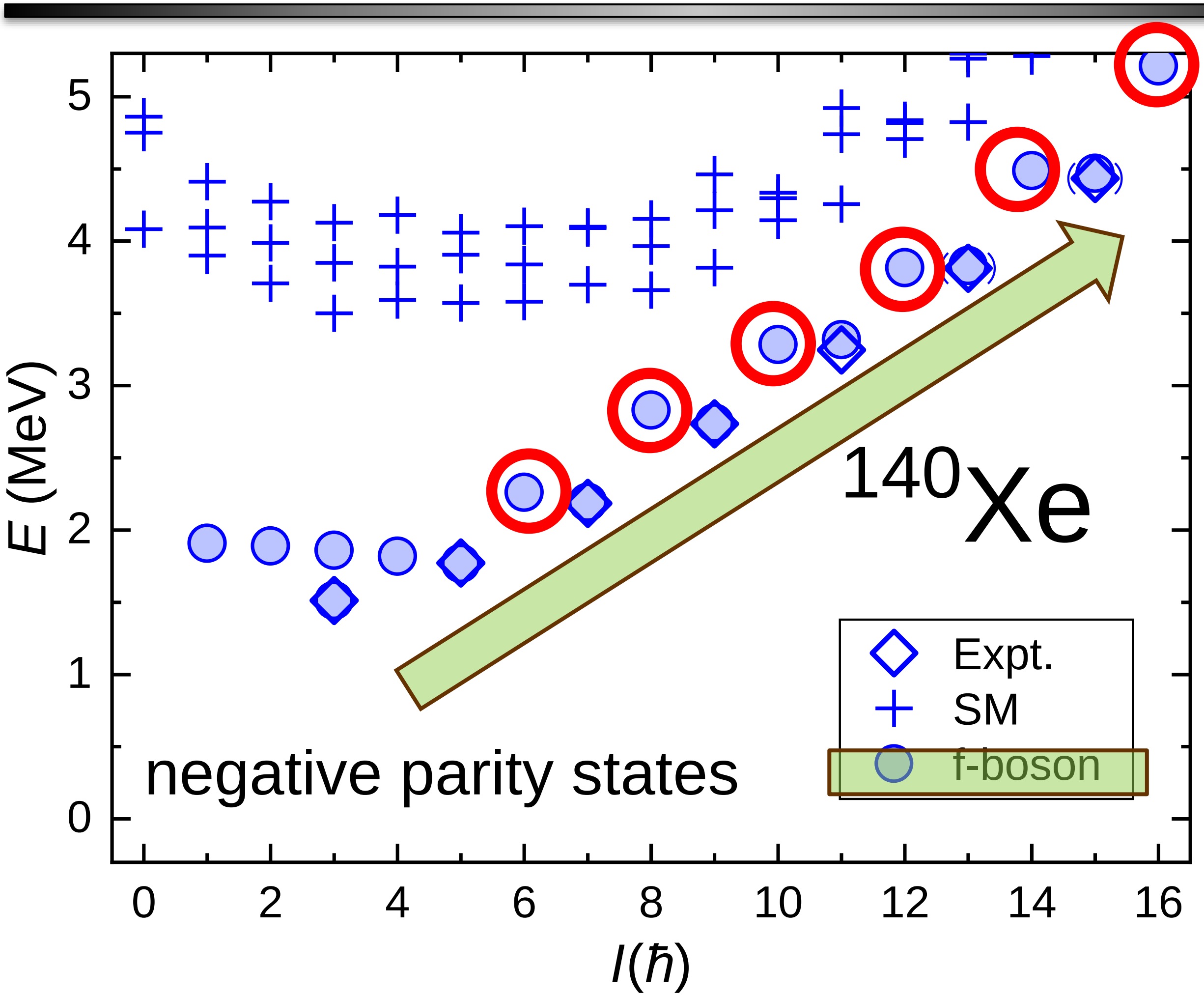
Octupole phonon model

Negative parity states in ^{140}Xe (pure SM)



Octupole phonon model

^{140}Xe with one octupole phonon



f-boson energy

$$\varepsilon_f + \frac{1}{2}\alpha\left[J(J+1) - I_k(I_k+1) - 12\right]$$

However, two essential problems to be solved for us to go further

1. SM calculations are hard to carry out for the valence neutrons more than 5 because of our computational feasibility

2. Energies of the Lowest 1^- octupole vibrational states are not well reproduced in the present model

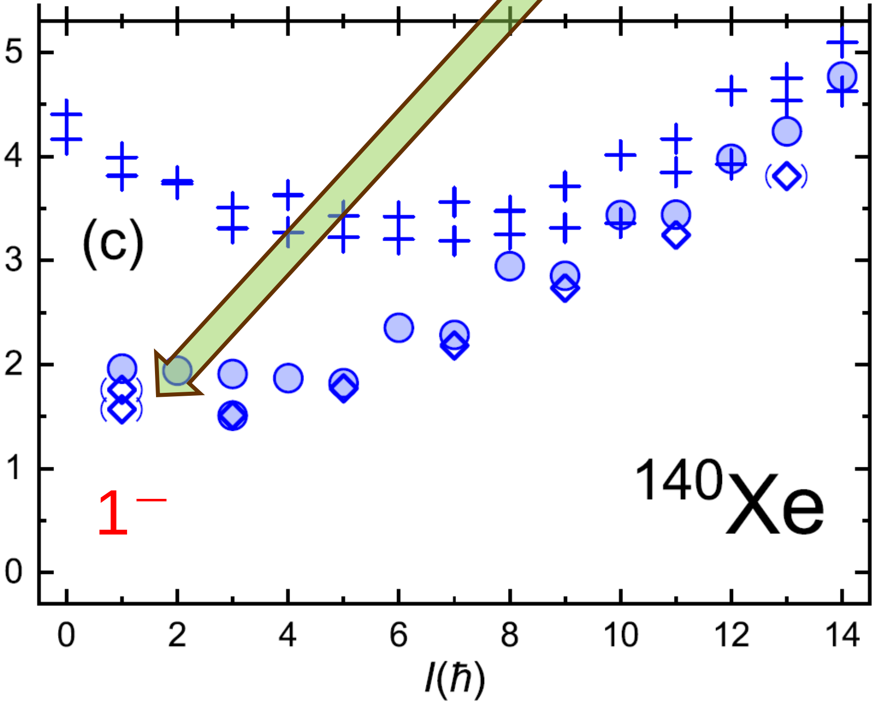
➡

A new model (method) is necessary

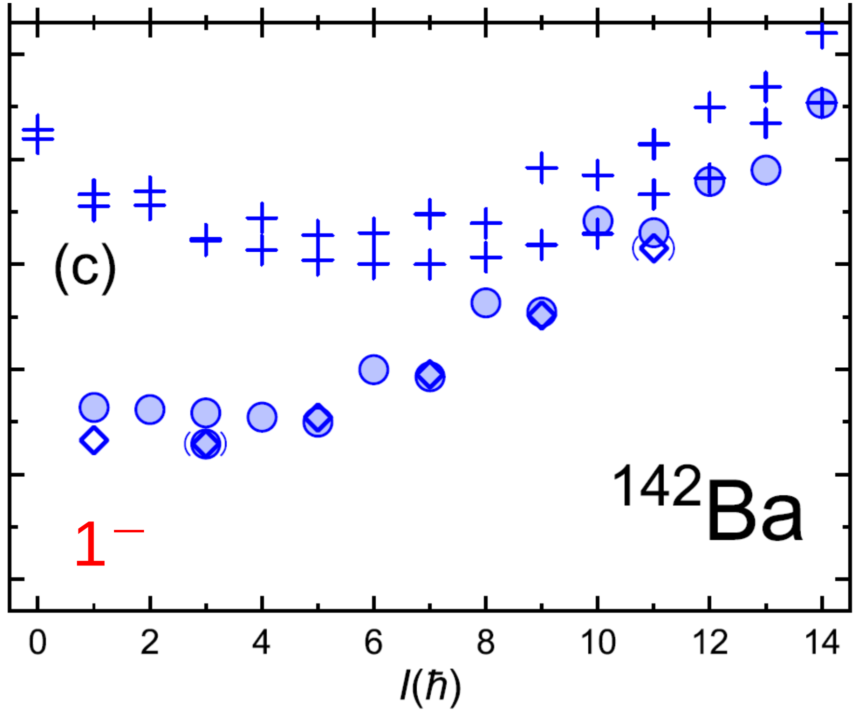
The first 1⁻ states are not well described

A. Yagi et al, PRC **105**, 044325 (2022)

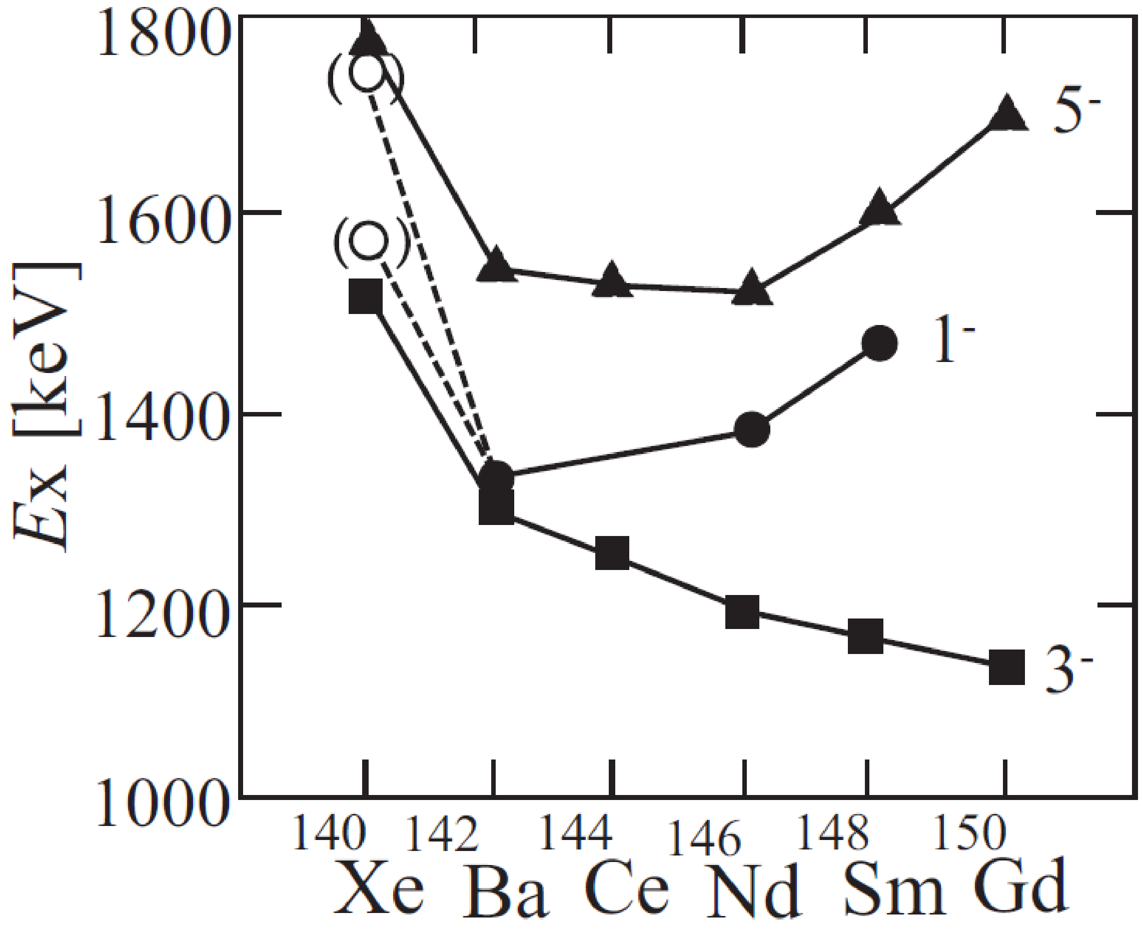
Z=54, N=86



Z=56, N=86



Systematics of excitation energies of octupole 1^-, 3^-, 5^- states in N=86 isotones



N=86 isotones

A. Yagi et al., PRC105, 044325(2022)

New octupole phonon model
model

Phenomenological *octupole phonon model*

$$\hat{H} = \hat{H}_V + \hat{H}_f + \hat{H}_{V-f}$$

$\boldsymbol{H}_V$: Valence hamiltonian

$$E_R^\pi = \left\langle R^\pi \middle| \hat{H}_V \middle| R^\pi \right\rangle$$

$\left| R^\pi \right\rangle$: Yrast states with spin-parity R^π

We adopt experimental energies for E_R^π

Octupole phonon excitation energy $\hat{H}_f = \varepsilon_f f^\dagger \cdot \tilde{f}$

Simplified dipole-dipole interaction $\hat{H}_{SM-f} = \alpha\, \boldsymbol{I}_V \cdot \boldsymbol{L}_f + \beta\, \boldsymbol{Q}_V \cdot \boldsymbol{Q}_f$

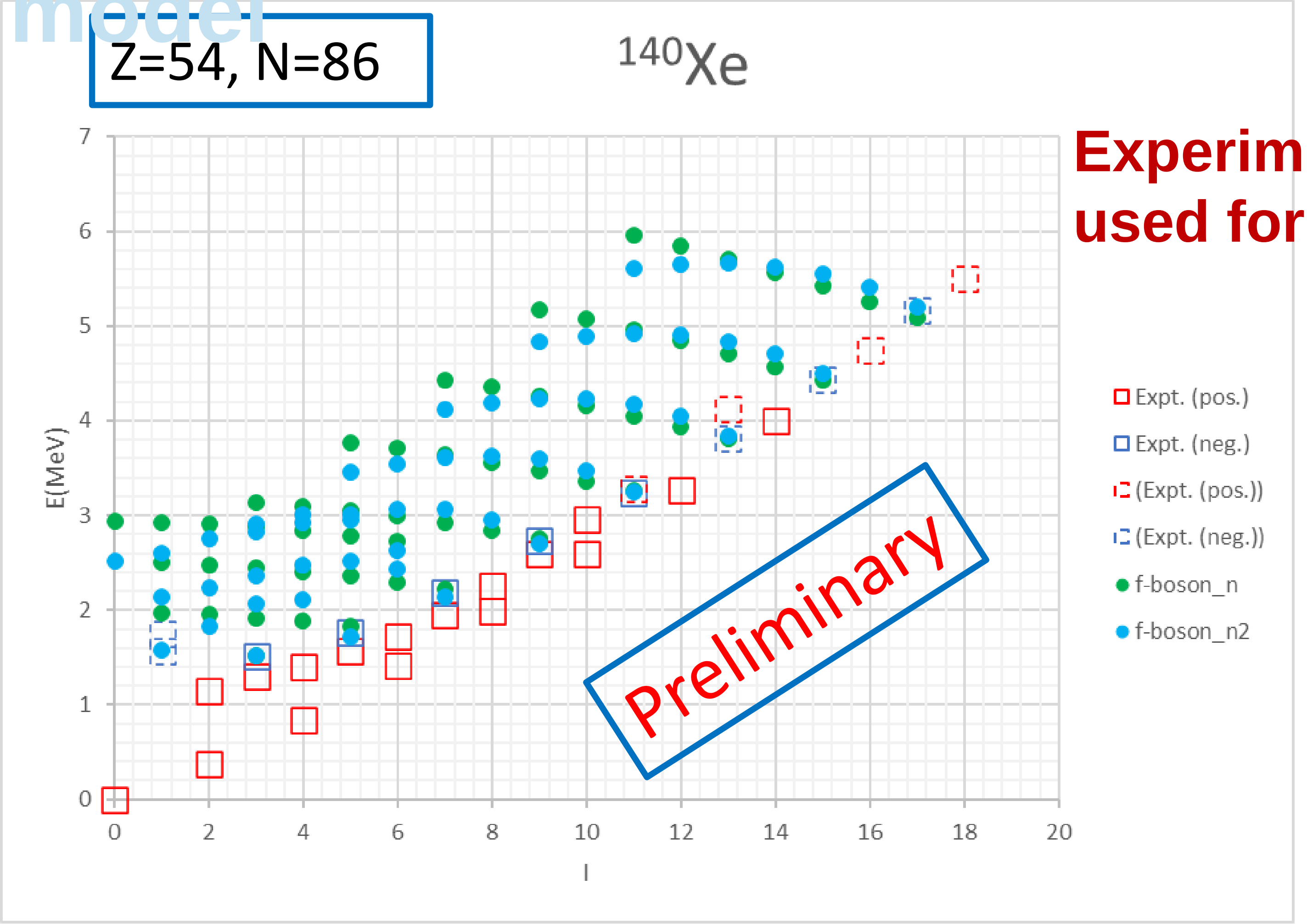
$\boldsymbol{Q}_{SM}$: Quadruple operator for valence states

$\boldsymbol{Q}_f$: *f*-boson Quadrupole operator

$$E_f\left(R^\pi, f; I\right) = E_{\text{exp.}}\left(R^\pi\right) + \varepsilon_f + \frac{1}{2}\alpha\left[I\left(I+1\right) - R\left(R+1\right) - 12\right] + \beta\left(-1\right)^{R+3+I}\begin{Bmatrix} R & 3 & I \\ 3 & R & 2 \end{Bmatrix}$$

New octupole phonon model

model



Experimental energies used for yrast states

Dipole term only

$\alpha = -0.01, \beta=0$

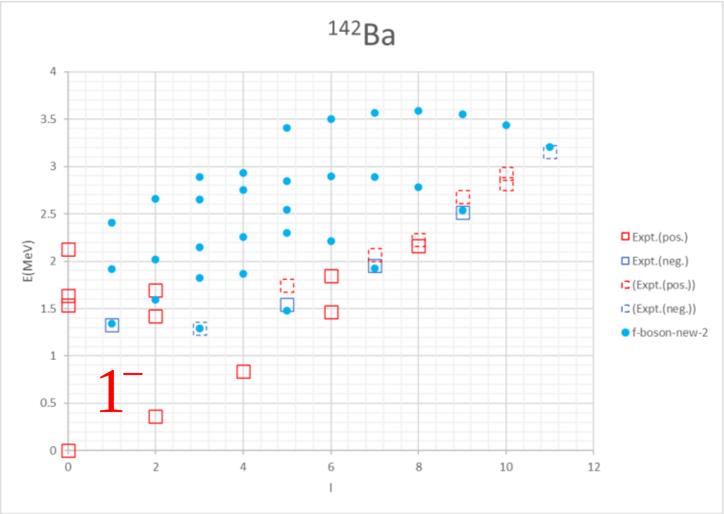
Dipole+ Quadrupole terms

$\alpha = -0.005, \beta=-2.5$

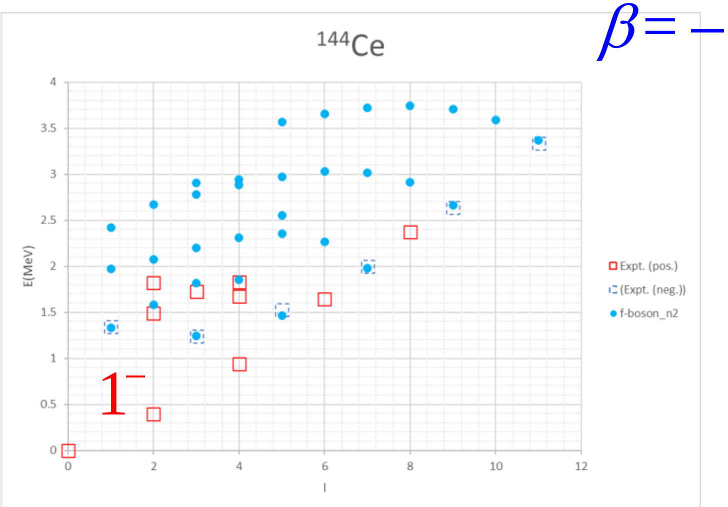
$$\alpha = -0.005$$

$$\beta = -2.5$$

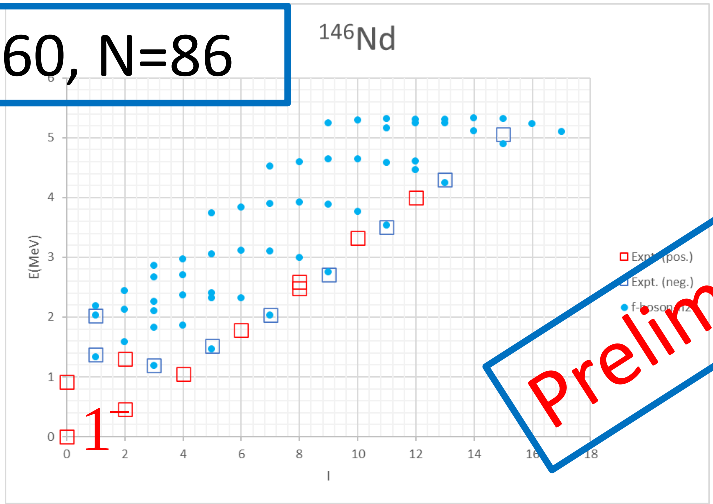
Z=56, N=86



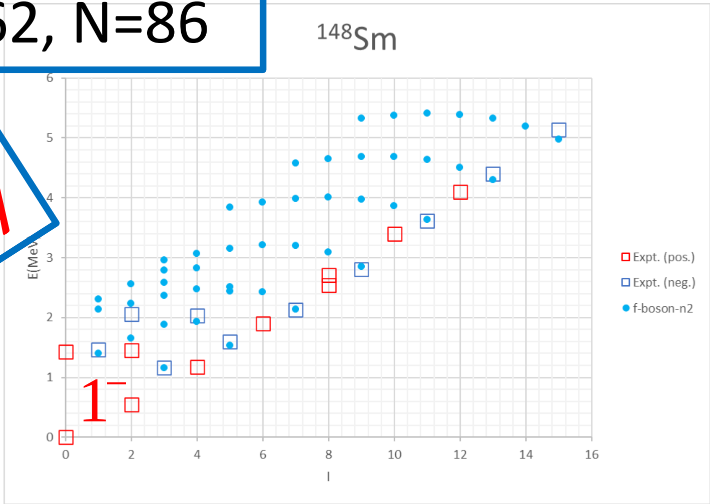
Z=58, N=86



Z=60, N=86



Z=62, N=86



Preliminary

Grand Summary

SM summary

- We have carried out the shell model calculation for nuclei beyond ^{132}Sn (North-East region)

  Target nuclei : Even-even, odd-mass, and doubly-odd nuclei for Xe, Cs, Ba isotopes up to mass 142

- Energy levels and electromagnetic properties are calculated
- We have obtained good agreements with the experimental data except octupole corelated states

- We have extended our framework including an octupole phonon and succeeded in reproducing the octupole vibrational band

Summary continues

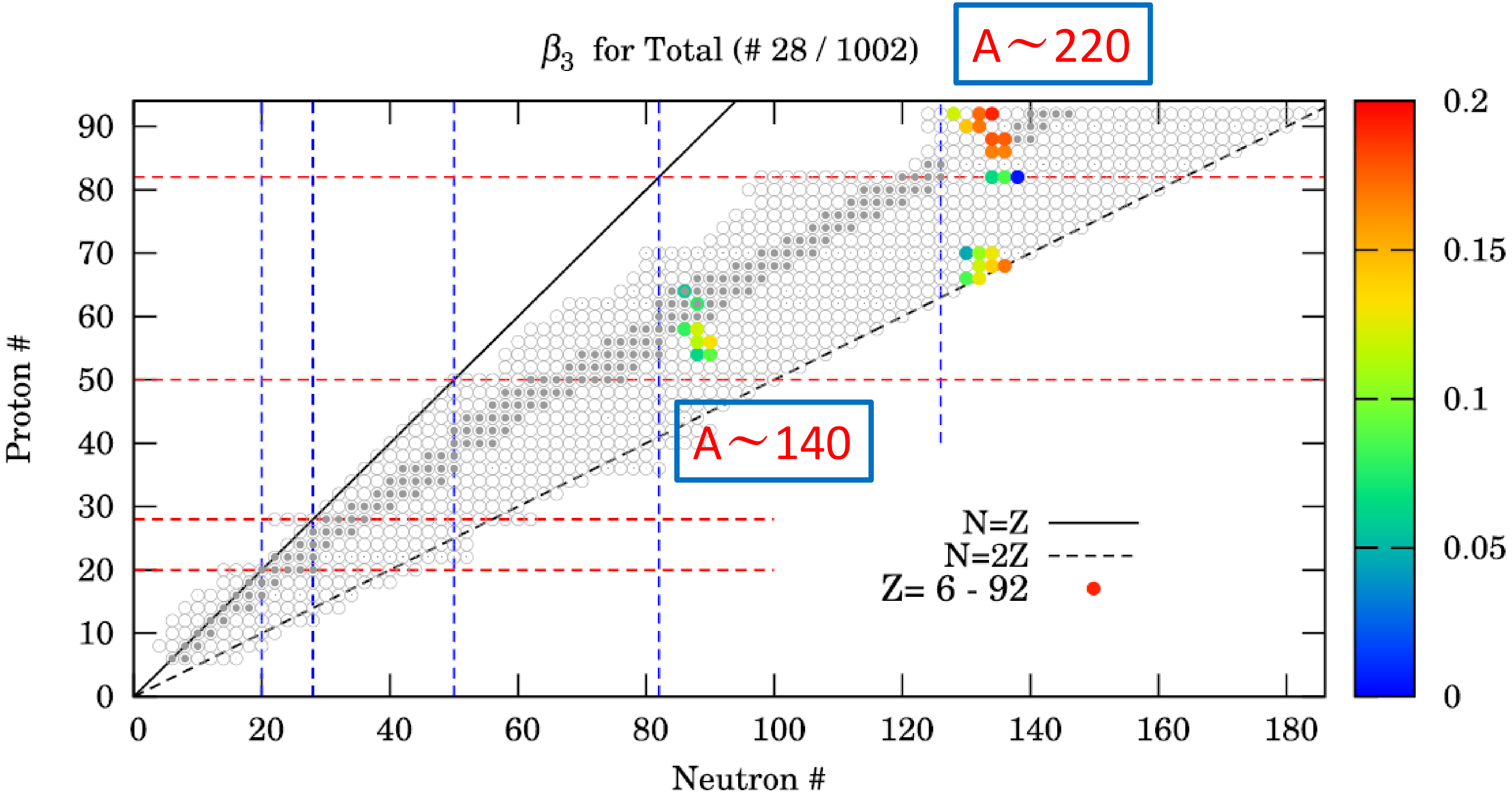
- ◆ We have proposed a new model without using the SM results by making use of the energies of the experimental yrast states for those nuclei that cannot be studied in the shell model framework.

- ◆ The model successfully reproduces the low-lying octupole phonon states including 1^- states.

Big question

- ◆ How far can we go using only one octupole phonon?

A hint may come from the following work



β_3 for Total (# 28 / 1002)

A～220

A～140

Shuichiro Ebata and Takashi Nakatsukasa,
Phys. Scr. 92 (2017) 064005