Microscopic description of large-amplitude shape dynamics in neutron-rich Mg isotopes

Nobuo Hinohara

RIKEN Nishina Center

Kenichi Yoshida (RIKEN)
Koichi Sato (Kyoto Univ. / RIKEN)
Takashi Nakatsukasa (RIKEN)
Masayuki Matsuo (Niigata Univ.)
Kenichi Matsuyanagi (RIKEN/YITP,Kyoto Univ.)

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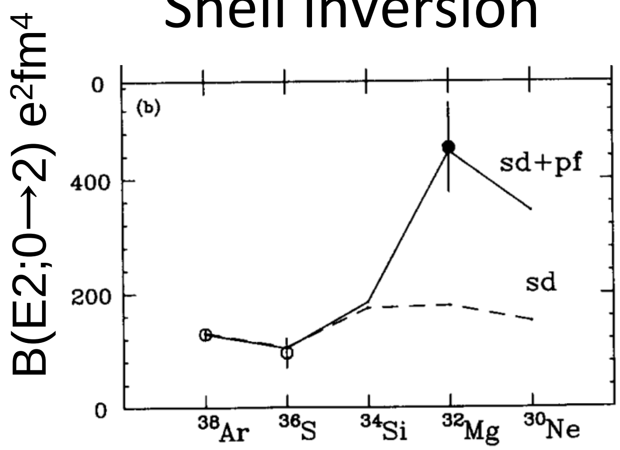
Magicity around N=20

- Low-lying 2^+ state: 885keV(^{32}Mg), 659keV(^{34}Mg)
- Large $B(E2;0^+\rightarrow2^+)$: 447e^2fm^4(^{32}Mg), 541e^2fm^4(^{34}Mg)

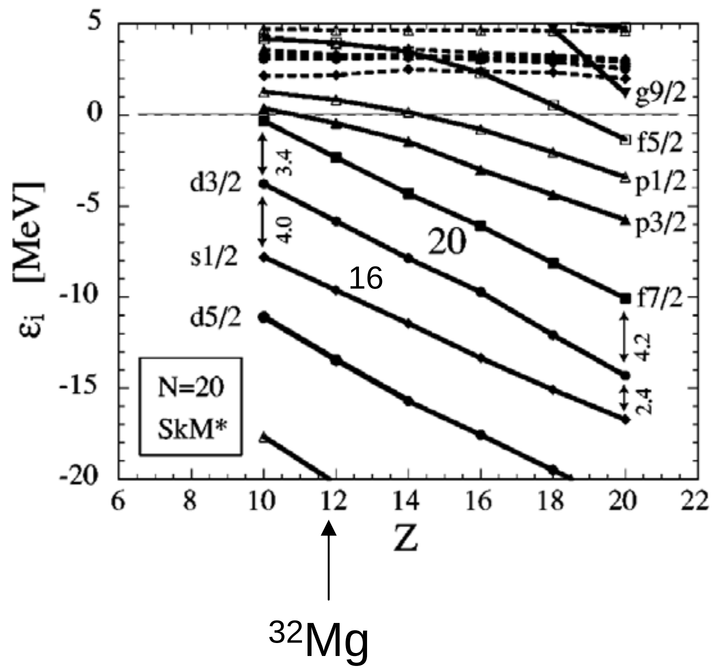
Breaking of the N=20 spherical magic number

Shell inversion



Motobayashi et al.,PLB**346**(1995)9

HF single-particle energy

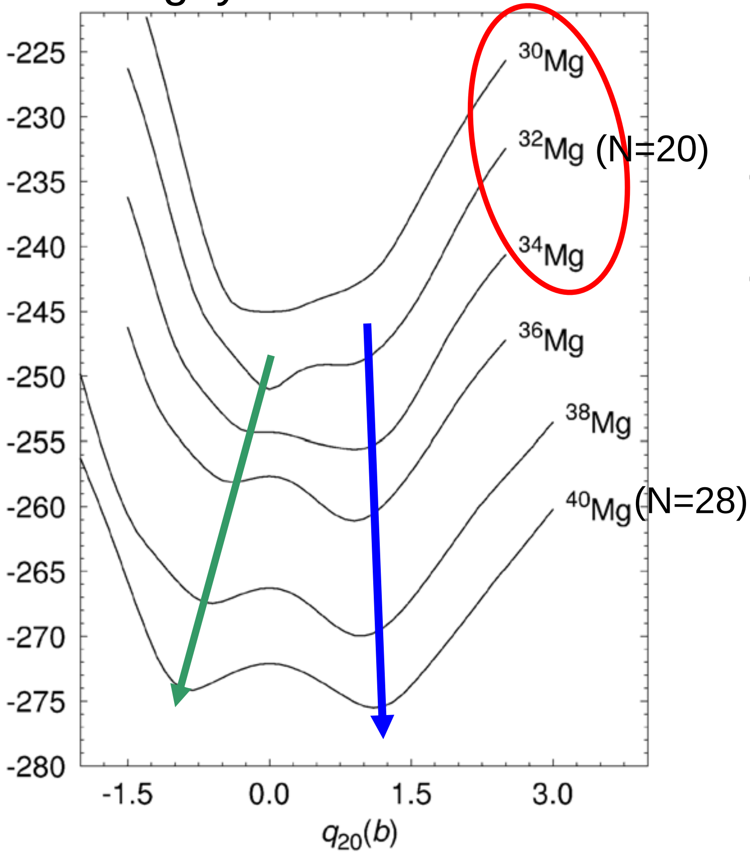


Yamagami and Giai PRC**69**, 034301(2004)

Deformation around N=20

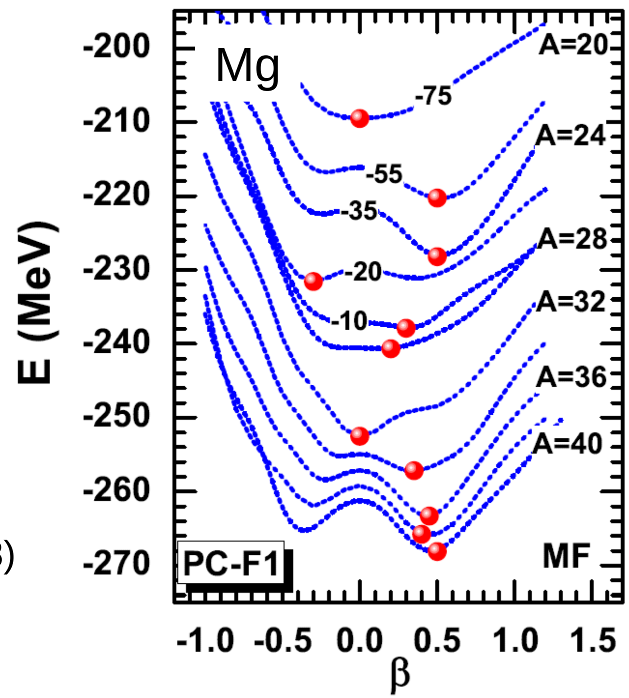
- Onset of deformation

Gogny D1S



Rodríguez-Guzmán et al., NPA**709**(2002)201

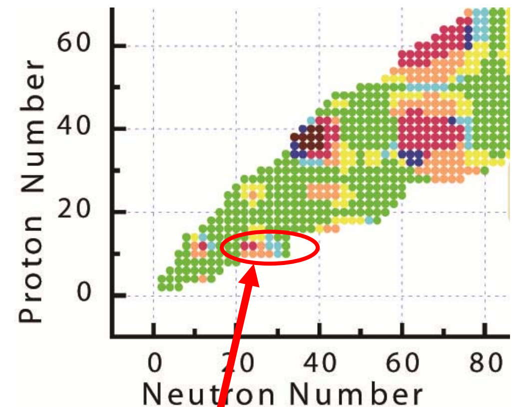
RMF+BCS



Yao et al., arXiv:1006.1400

Stoitsov et al., PRC**68**(2003) 054312

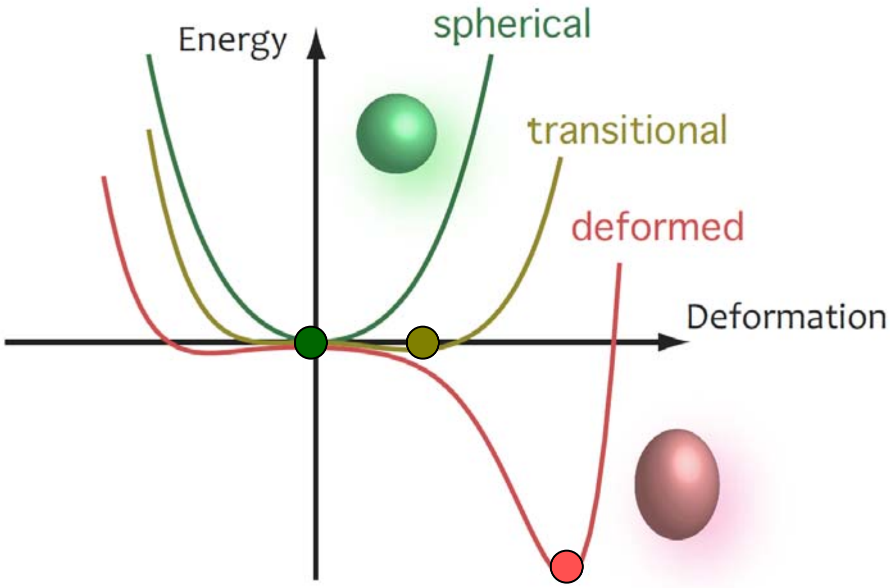
Skyrme



Neutron-rich Mg region between N=20 and 28

Beyond small-amplitude vib. of mean-field

Potential energy surfaces around ^{32}Mg are soft against deformation



Quantum correlation beyond mean-field (HFB) + small-amplitude vibration (QRPA) plays essential role in low-lying states (large-amplitude collective motion)

Microscopic theories of LACM

- Boson expansion method / Self-consistent Collective Coordinate method
- Generator coordinate method (configuration mixing)
- Adiabatic TDHFB theories (collective Hamiltonian)

Theoretical framework

Five-dimensional quadrupole collective Hamiltonian

quadrupole amplitudes: $\alpha_{2\mu} \leftarrow\rightarrow \beta, \gamma, \Omega=(\phi, \theta, \Psi)$

$$\mathcal{H}_{\text{coll}} = V(\beta,\gamma) + T_{\text{vib}} + T_{\text{rot}}$$

$$T_{\text{vib}} = \frac{1}{2} D_{\beta\beta}(\beta,\gamma)\dot{\beta}^2 + D_{\beta\gamma}(\beta,\gamma)\dot{\beta}\dot{\gamma} + \frac{1}{2} D_{\gamma\gamma}(\beta,\gamma)\dot{\gamma}^2$$

$$T_{\text{rot}} = \frac{1}{2}\sum_{k=1}^{3} \mathcal{J}_k(\beta,\gamma)\omega_k^2$$

V(β, γ)	collective potential
D(β, γ)	vibrational collective mass
J(β, γ)	rotational moment of inertia

- Classical Hamiltonian for adiabatic quadrupole collective motion
- Small-amplitude limit: surface vib. collective rotation, β-vib., γ-vib. γ-unstable …

Requantization of collective Hamiltonian

Boundary conditions:

Kumar and Baranger NPA**92** 608 (1967)

→ Excitation energies, collective wave functions, quadrupole moments, E2 transitions …

Microscopic derivations of functions in collective Hamiltonian

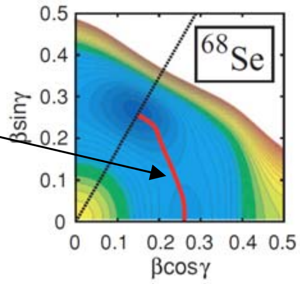
Microscopic theory of large-amplitude collective motion

"Adiabatic self-consistent collective coordinate (ASCC) method"

Matsuo et al., Prog.Theor.Phys.**103**,959 (2000)
NH et al., Prog.Theor.Phys.**117**,451 (2007)

- Theory to determine **"collective path/subspace"** in TDHFB phase space
- Effect of time-odd component on collective mass

Prog. Theor. Phys. **115** 567 (2006)



one-dimensional collective path
PRC**80**, 014305 (2009)

ASCC for two-dimensional collective subspace (q_1,q_2,p_1,p_2)

assumptions and approximations

CHFB+LQRPA method

PRC submitted, arXiv:1004.5544

Constrained Hartree-Fock-Bogoliubov equation → **V(β, γ)**

Local QRPA equations (for vibration) → **D(β, γ)**

Local QRPA equations for rotation → **J(β, γ)**

- QRPA on top of CHFB state
- Hamiltonian used in QRPA also contains constraint terms

Comparison with other 5D Hamiltonian approaches

	Potential energy correction (GOA)	**vibrational collective mass**	**rotational moment of inertia**	**effective interaction**
CHFB + LQRPA	--	**LQRPA (Thouless-Valatin)**	**LQRPA (Thouless-Valatin)**	P+Q with quadrupole pairing
RMF group	vib. + rot. ZPE (IB)	Inglis-Belyaev	Inglis-Belyaev (Scaled)	**RMF+BCS (PC-F1)**
Skyrme group	--	Inglis-Belyaev	Inglis-Belyaev (Scaled)	**Skyrme + const. G pairing**
Gogny group	vib. + rot. ZPE (IB)	Inglis-Belyaev	**Thouless-Valatin (cranked field)**	**Gogny D1S**

- RMF group: Li et al., Phys.Rev.**C81**, 034316 (2010)
- Gogny group: Delaroche et al., Phys. Rev. **C81**, 014303 (2010)
- Skyrme group: Próchniak et al., J.Phys.**G36**,123101 (2009)

Inglis-Belyaev inertia does not consider the effect of time-odd component of mean-field

Calculation Details

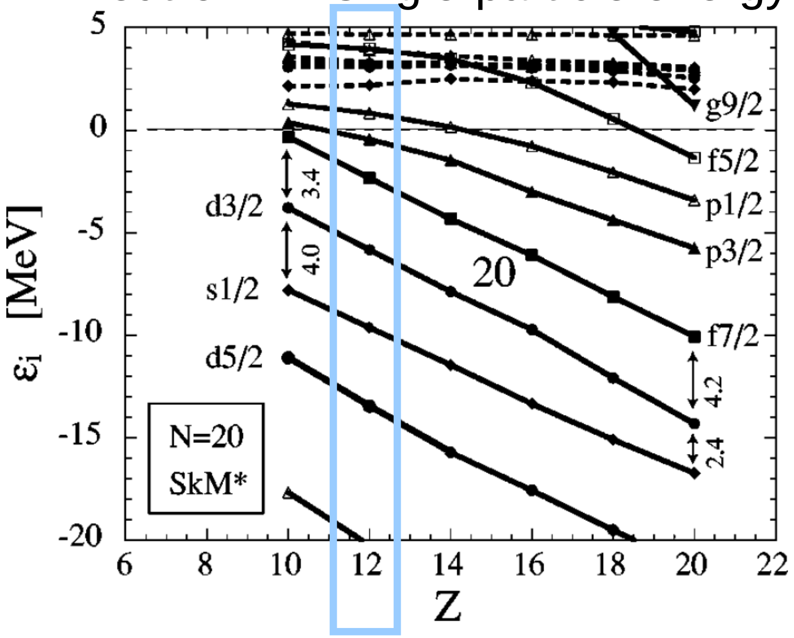
- **Nuclei calculated**
  ^{30,32,34}Mg (N = 18, 20, 22, Z = 12)
- **Microscopic Hamiltonian (Pairing + Quadrupole Model)**
  Single-particle energy + pairing (Monopole, Quadrupole)
  + quadrupole (p-h) force
- **Single-particle model space**
  harmonic oscillator two major shells (*sd* + *pf* shells)
- **Parameters**
  - single-particle energies (neutrons and protons)

s1/2	d3/2	d5/2	p1/2	p3/2	f5/2	f7/2
-9.8	-5.9	-13.5	0.7	-0.5	3.8	-2.3

(MeV)

SkM* spherical single-particle energy for ^{32}Mg
Yamagami and Giai Phys. Rev. **C69**, 034301 (2004)
is used for $^{30-34}$Mg

neutron HF single-particle energy



Calculation Details

- Parameters
  - Interaction strength
    - **neutron and proton monopole pairing**

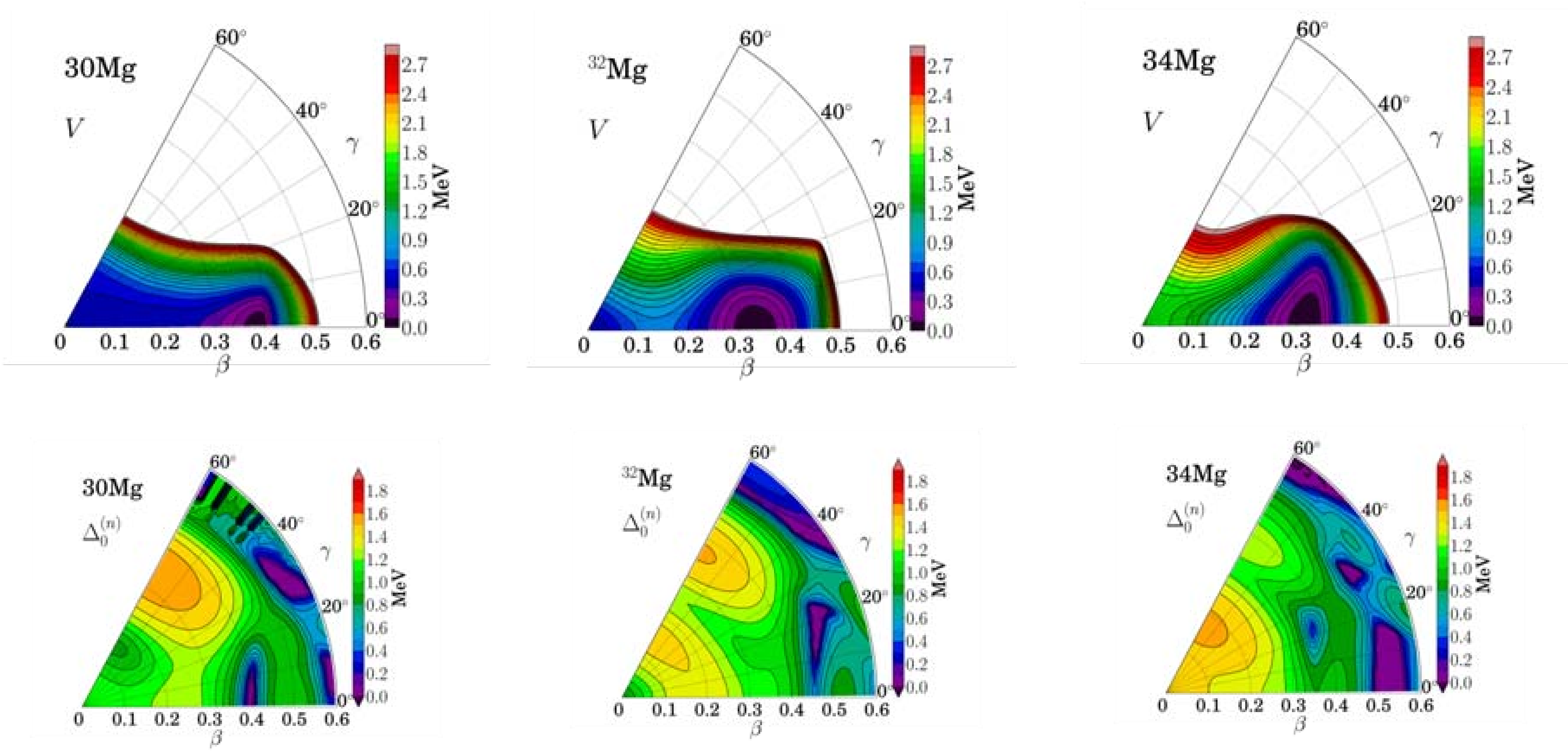
      ^{32}Mg: adjusted to reproduce pairing gaps of Yamagami et al. (SkM*+mixed pairing) at spherical shape ($\Delta_n \sim 0.9$ MeV, $\Delta_p \sim 0.8$ MeV)

      ^{30,34}Mg: with A^{-1} dependence
    - **quadrupole p-h interaction strength**

      ^{32}Mg: adjusted to reproduce experimental 2_1^+ energy after quantization

      ^{30,34}Mg: with $A^{-5/3}$ dependence
    - **quadrupole pairing strength G_2**:
      - $G_2 = G_2^{self}$ (self-consistent value) Sakamoto et al. PLB245 (1990) 321
  - Effective charges
    - $e_n = 0.8$, $e_p = 1.8$ (adjusted to experimental B(E2;2→0) in ^{32}Mg)

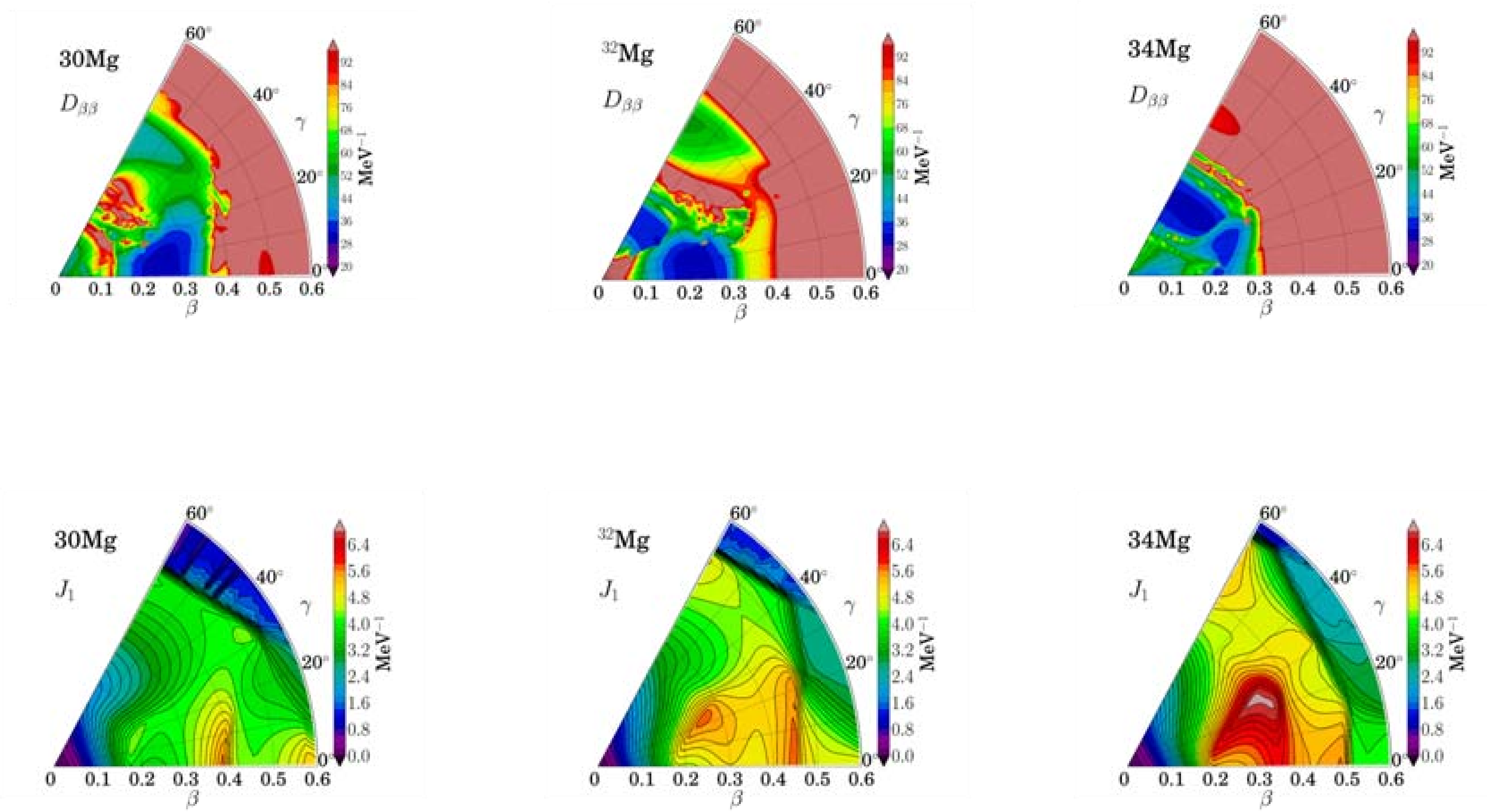
Collective potentials V(β,γ), neutron pairing gap $\Delta_n(\beta,\gamma)$



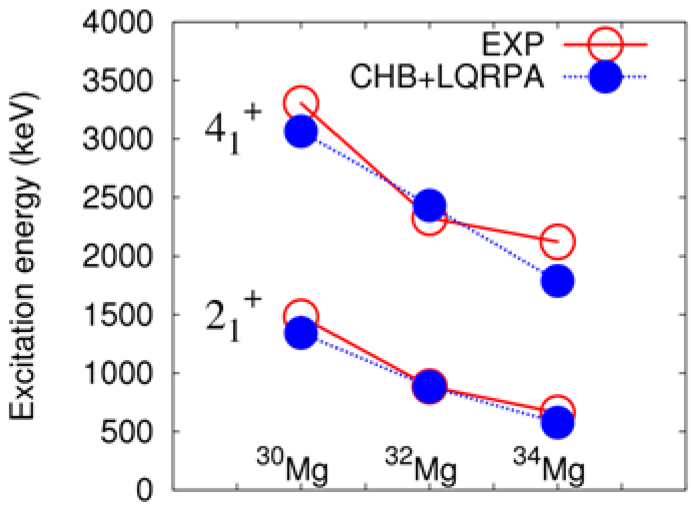
- prolate minima are found in all three nuclei

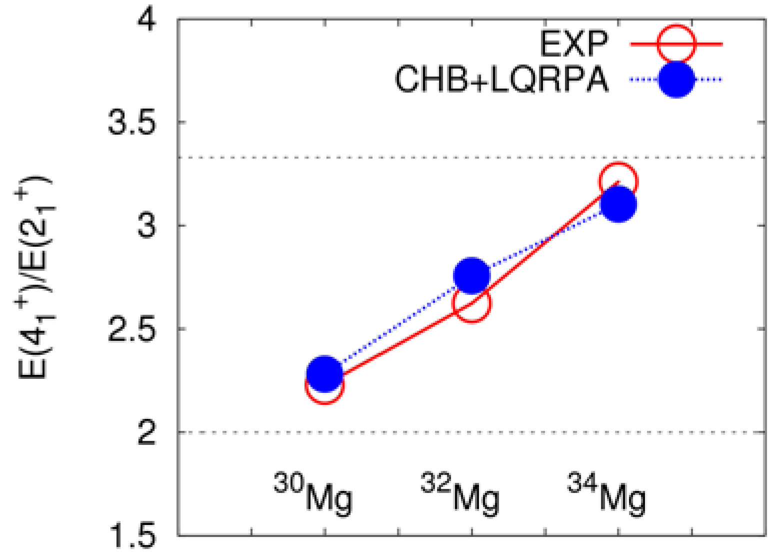
- ^{30}Mg: extremely soft in β direction
- ^{32}Mg: spherical and prolate shape coexistence
- ^{34}Mg: soft in γ dirction

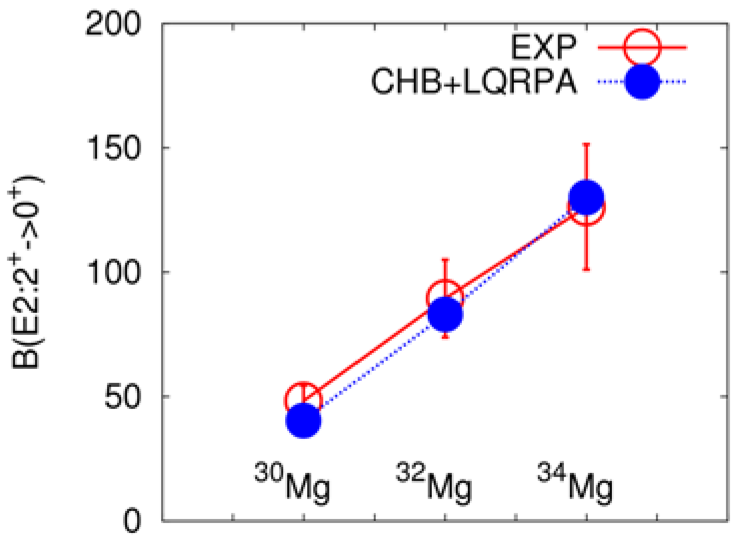
Inertial functions (mass $D_{\beta\beta}(\beta,\gamma)$ / MoI $J_1(\beta,\gamma)$)



Ground bands







^{30}Mg: assume 3303 keV to be 4^+
^{32}Mg: Takeuchi et al. PRC79 (2009) 054319
^{34}Mg: Yoneda et al. PLB499 (2001) 233

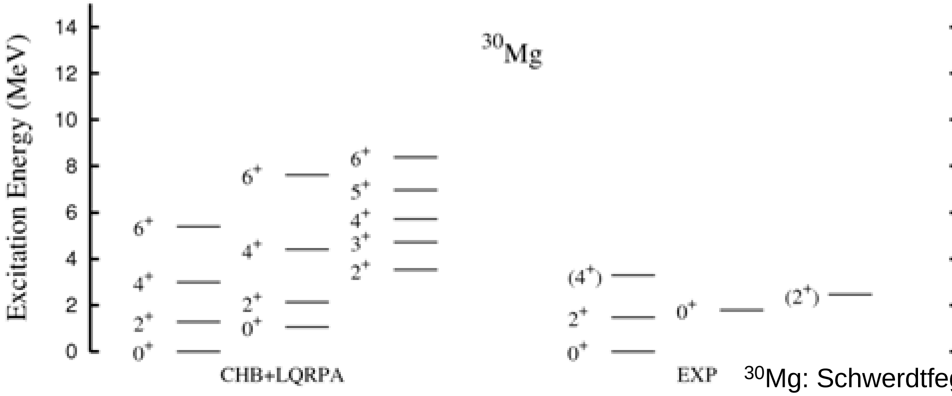
M_n/M_p / (N/Z)

	^{30}Mg	^{32}Mg	^{34}Mg
$2^+ \rightarrow 0^+$	0.789	0.815	0.807

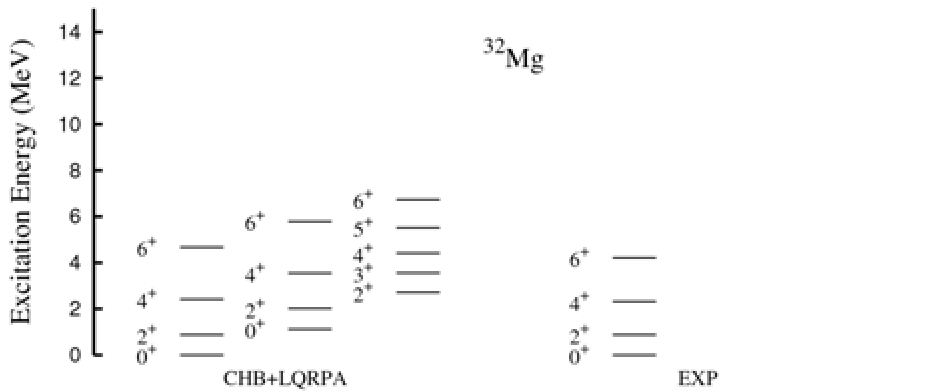
0.84(15)
EXP, Takeuchi et al.

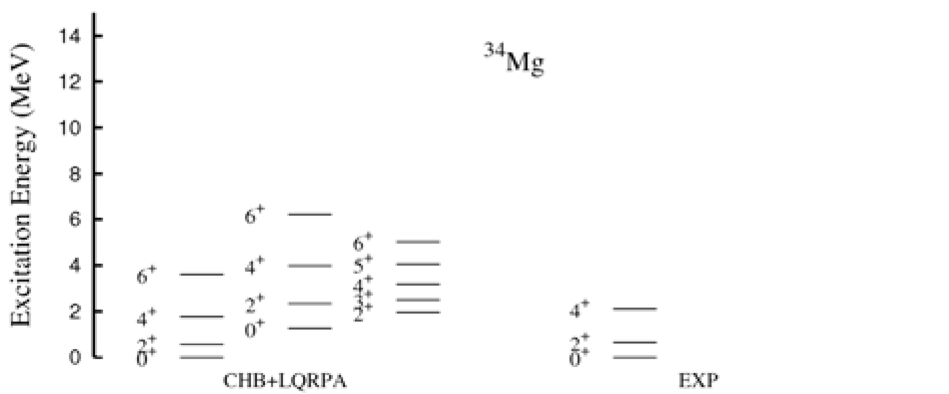
B(E2)
^{30}Mg: Niedermaier et al. PRL**94** (2005) 172501
^{32}Mg: Motobayashi et al. PLB**346** (1995) 9
^{34}Mg: Iwasaki et al. PLB**522** (2001) 227.

Energy spectra

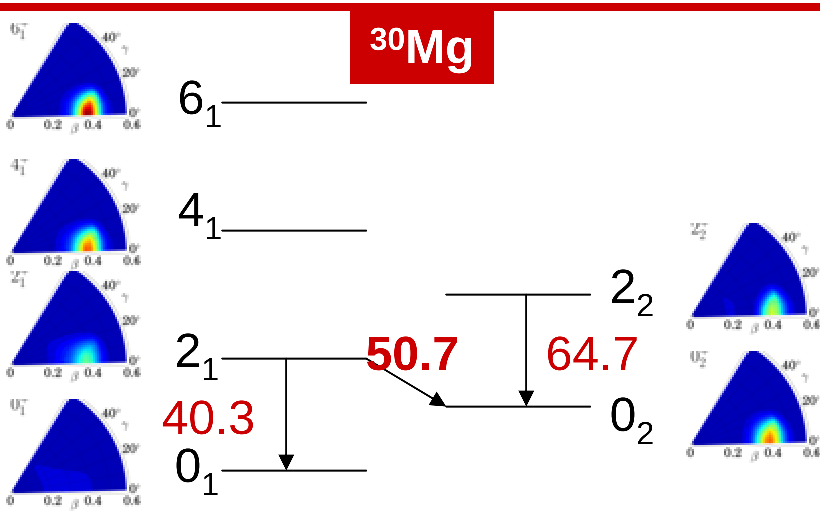


^{30}Mg: Schwerdtfeger et al., PRL103, 012501 (2009)



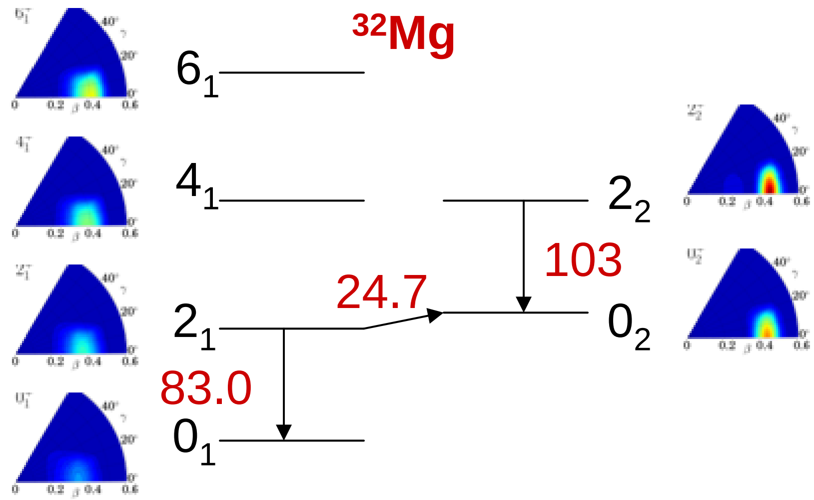


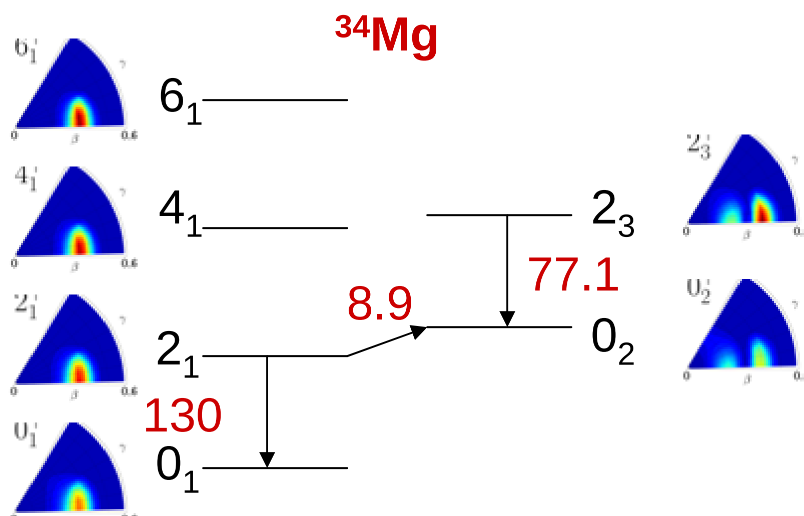
Shape mixing properties



B(E2;2_1^+→0_2^+) > B(E2;2_1^+→0_1^+)

- ☐ shape change in ground band (spherical → prolate)
- ☐ shape mixing in 0^+, 2^+ states





Conclusion

- We have analyzed the low-lying states of $^{30,32,34}Mg$ isotopes using the 5D quadrupole collective Hamiltonian constructed with the **CHFB + LQRPA method**.
- Properties of the ground band (excitation energies, B(E2)) are well reproduced within one adjustable parameter in the model (and effective charges).
- Shape mixing properties are analyzed. Strong shape mixing is expected in 0^+ and 2^+ state of ^{30}Mg.