Description of multi-phonon states using ab initio PGCM calculations

ESNT Workshop
Nuclear Excitations and Resonances

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Regular Article -Theoretical Physics

Ab initio description of monopole resonances in light- and medium-mass nuclei

I. Technical aspects and uncertainties of ab initio PGCM calculations

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I. [EPJA (2024) 60, 133]
II. [EPJA (2024) 60, 134]
III. [EPJA (2024) 60, 155]
IV. [arXiv:2407.01325]

Outline

Introduction

- Physics case
- Existing ab initio methods

PGCM description of GRs

- Sum rule exhaustion
- Shape isomerism effects
- Comparison to experimental results

Multi-phonon states

- Monopole resonances in ^{46}Ti
- Quadrupole resonances in ^{40}Ca

Conclusions

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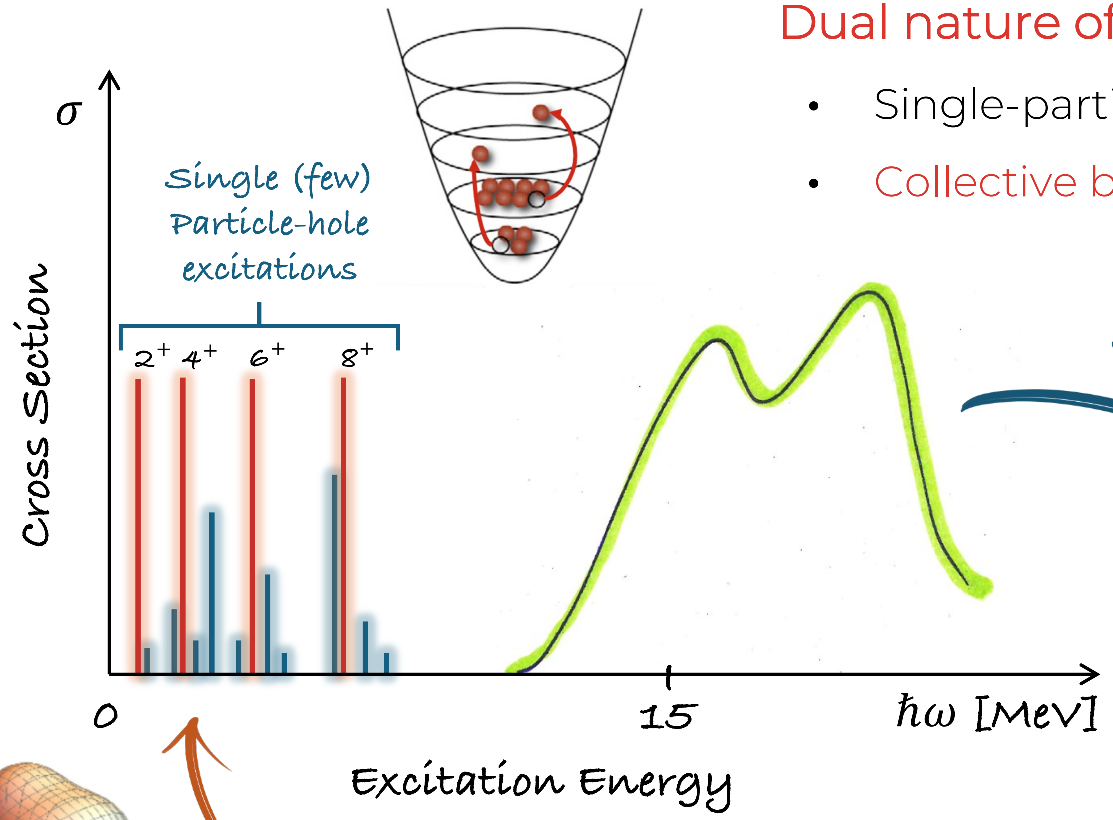
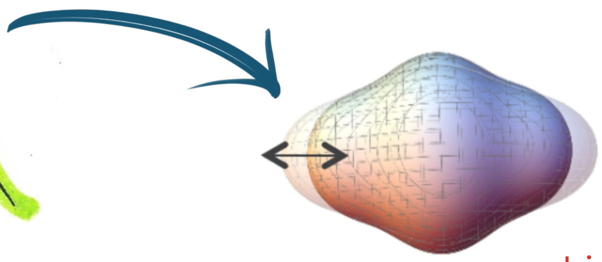
Giant Resonances

Dual nature of nucleus

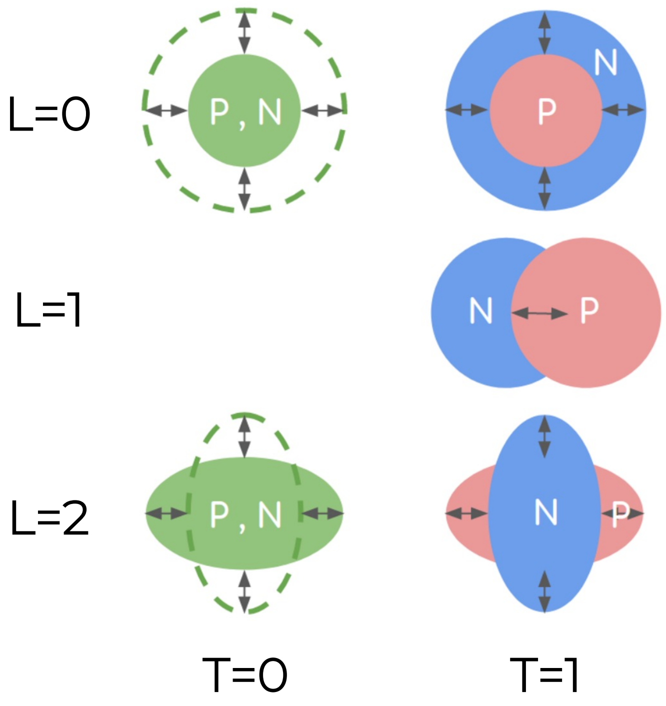
- Single-particle features
- Collective behaviour

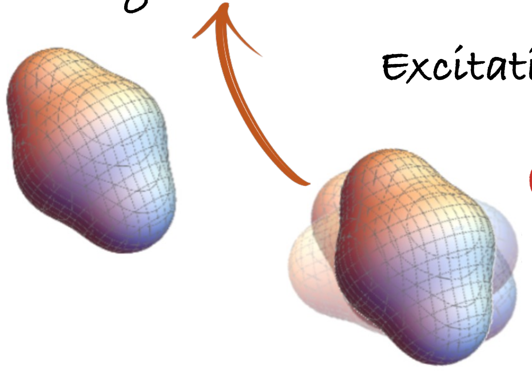


Giant Resonances



Liquid drop picture
vibrations, oscillations





(Rotations)

Giant Resonances (GRs)

clearest manifestation of collective motion

[Pictures from Dytrych et al., PRL, 2020]

Multi-phonon states

Commonly observed in low-lying nuclear vibrations (quadrupole)

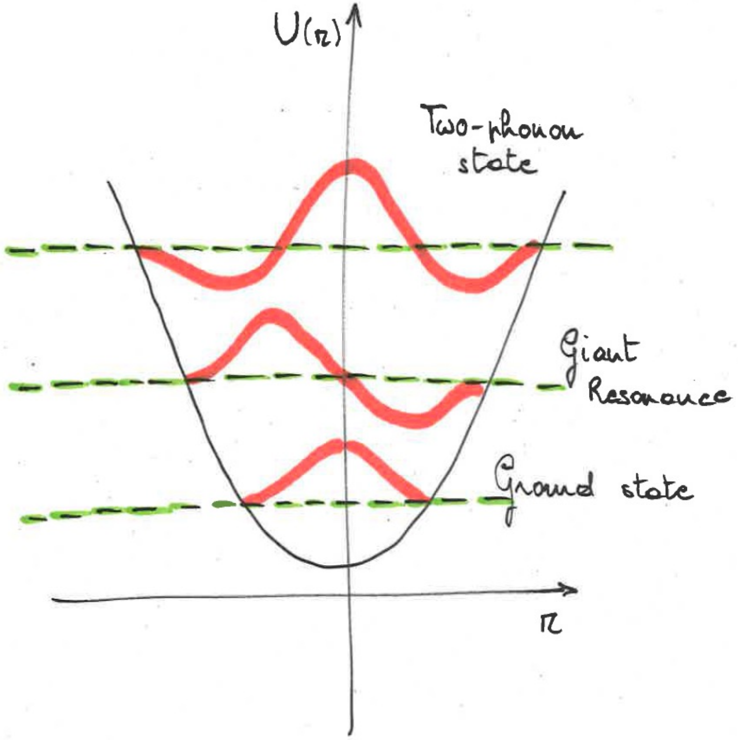
- Two-phonon triplets, three-phonon

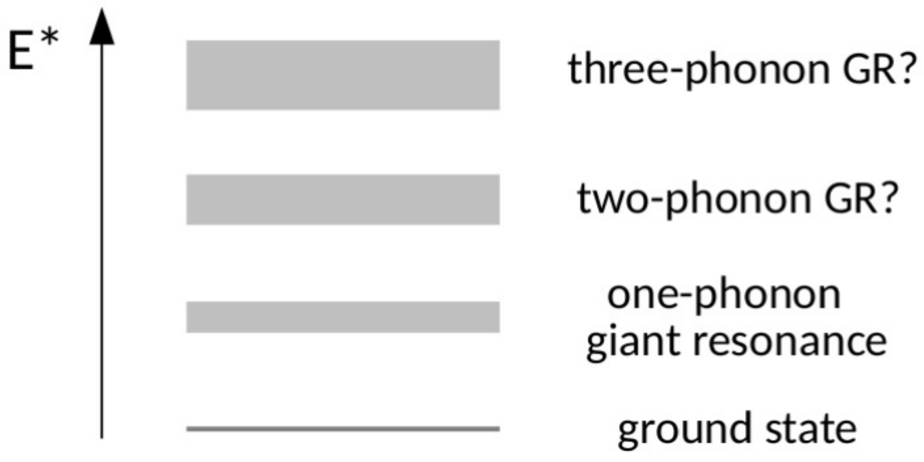
GRs can be thought as the first phonon of a collective excitation

- Do higher excitation quanta exist (multi-phonons) ?

If yes,

- are they harmonic? How strong the anharmonicities ?
- how large are the phonon-phonon interactions?
- do they set tensions with the Brink-Axel hypothesis?





Experiment

2nd phonon observed in multiple nuclei (IVGDR, ISGQR in ^{40}Ca)

3rd phonon possibly observed in two cases

Schmidt *et al.*, IVGDR in ^{136}Xe (1993), Fallot *et al.*, ISGQR in ^{40}Ca (2006)

Theory

- Ad hoc models, introduction of phonon d.o.f.
- TD-DFT [Marevic, Regnier and Lacroix, PRC 108, 014620 (2023)]

Theoretical ab initio tools

EOM and VS extensions

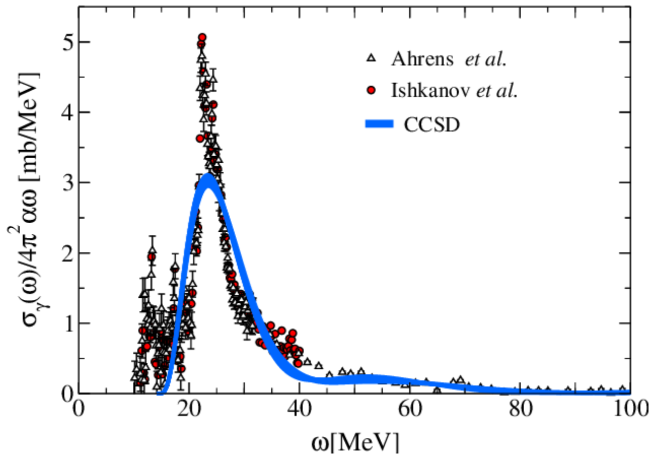
- **IMSRG** and **CC**
- Suited for **weakly-collective** excitations only

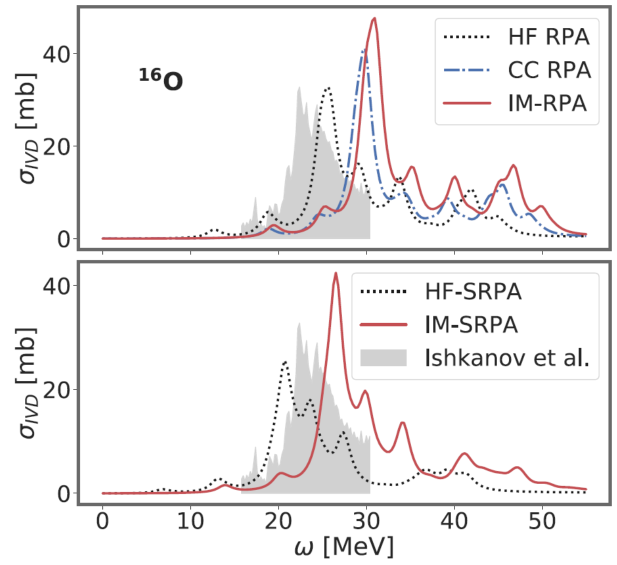
CC-LIT Lorenz integral transform (spherical)

SA-NCSM Application to deformed systems (^{20}Ne)

[Bacca, Barnea, Hagen, Orlandini, Papenbrock, PRL, 2013]

[Dytrych, Launey, Draayer, Maris, Vary et al., PRL, 2013]





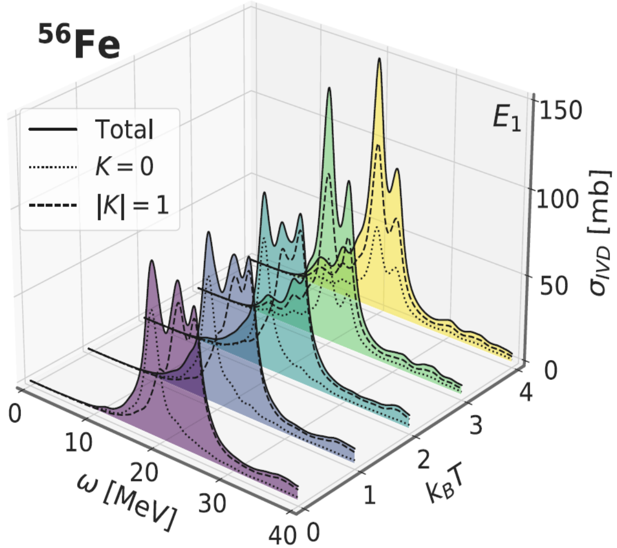
(Q)RPA

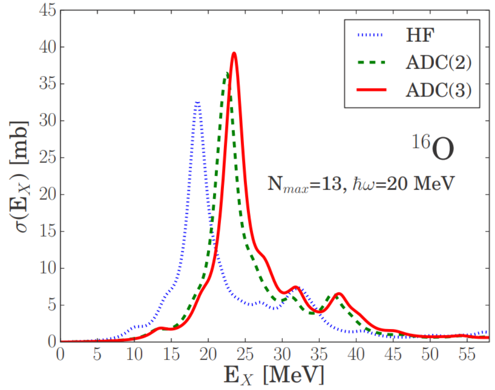
- Spherical (Q)RPA, 2nd RPA, CC-RPA, IMSRG-RPA, IMSRG-2nd RPA
- SCGF, RPA with dressed propagators
- (Q)RPA for axially- and triaxally-deformed systems

[R. Trippel, PhD Thesis, 2016]

[Barbieri, Raimondi, PRC, 2019]

[Beaujeault-Taudière, Frosini, Ebran, Duguet, Roth, Somà, PRC, 2023]





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Technical details

Ab initio PGCM numerical settings (systematic study in ^{46}Ti)

- Quantities expanded on harmonic oscillator basis (characterised by **ħω,** e_{max} , e_{3max})
- Family of chiral NN + in-medium 3N interactions (NLO, N2LO and N3LO)
  - T. Hüther, K. Vobig, K. Hebeler, R. Machleidt and R. Roth, "Family of chiral two-plus three-nucleon interactions for accurate nuclear structure studies", *Phys. Lett. B,* 808, 2020
  - In-vacuum SRG evolution (**α**=0.04 fm^4, **α**=0.08 fm^4)
  - M. Frosini, T. Duguet, B. Bally, Y. Beaujeault-Taudière, J.-P. Ebran and V. Somà, “In-medium k-body reduction of n-body operators”, *The European Physical Journal A*, *57*(4), 2021

Sum rules exhaustion

Different evaluation streategies for the moments

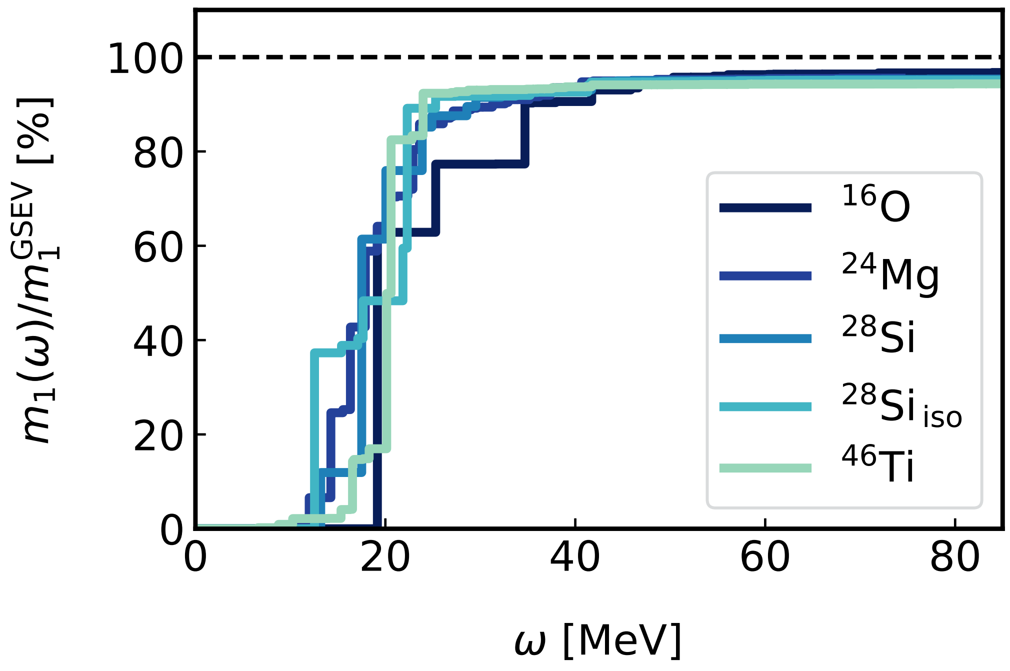
$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

$$m_k \equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega$$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2$$ → Must know excited states

6-7 % difference in PGCM

$$\equiv \langle \Psi_0 | \breve{M}_k(i,j) | \Psi_0 \rangle$$ → Ground state only



Complexity is shifted to the operator structure

$$\breve{M}_k(i,j) \equiv (-1)^i C_i C_j \qquad \forall \;\; k \geq 0$$

$$M_k(i,j) \equiv \frac{1}{2}(-1)^i [C_i, C_j] \;\; \text{if} \;\; k = 2n+1, \;\; n \in \mathbb{N}$$

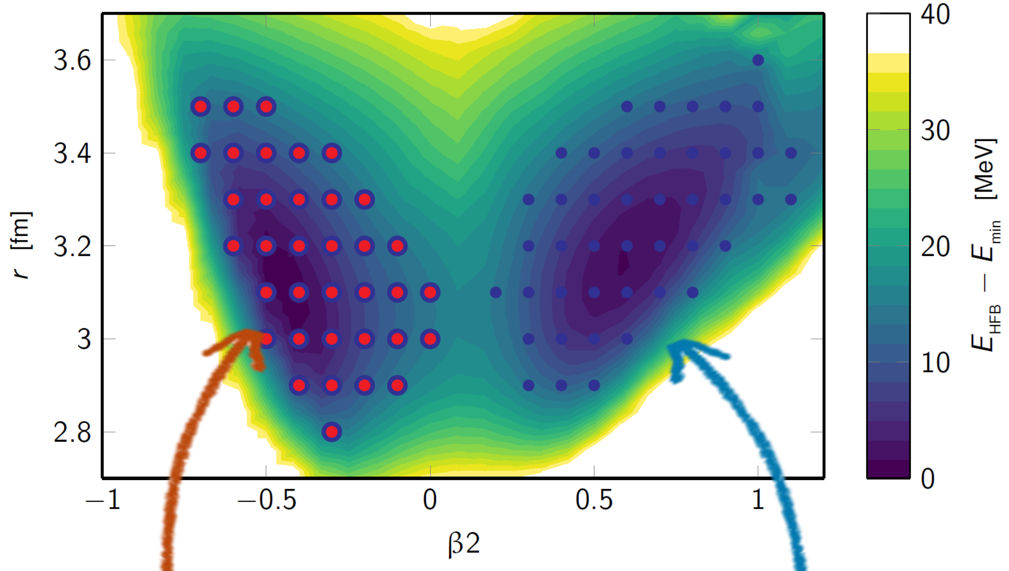
$$C_l \equiv \underbrace{[H,[H,...[H,[H}_{l \text{ times}},r^2]]...]]$$

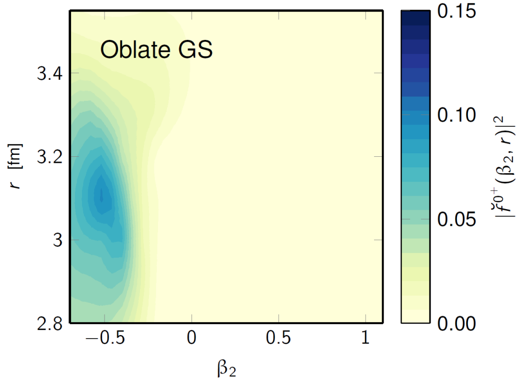
Many-body operators

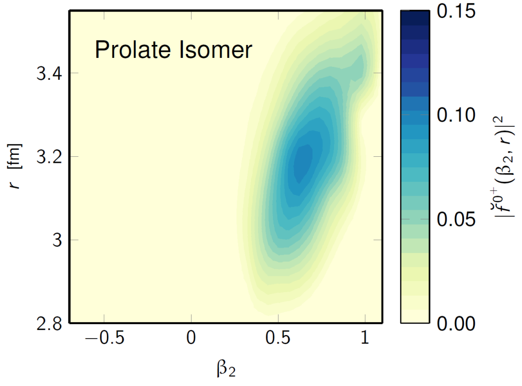
- Exact up to m_1 $\qquad H = H^{[1]} + H^{[2]}$

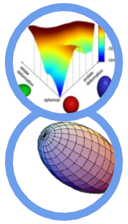
Shape coexistence effects in ^{28}Si

Total Energy Surface $E_{HFB}(\beta_2, r)$



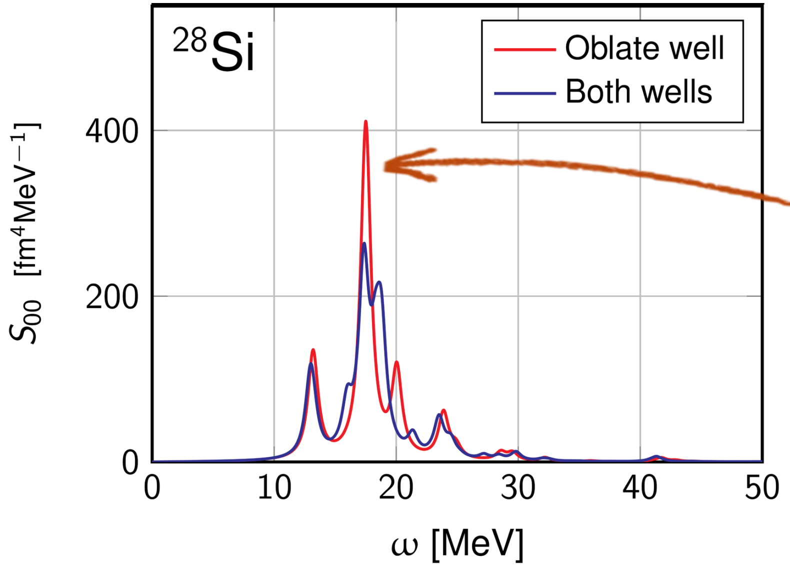




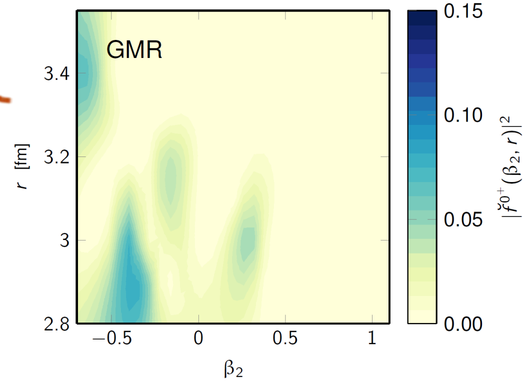


Shape coexistence [Jenkins et al., 2012]

Deformation



Radial vibration on oblate GS



- Oblate GS and prolate-shape isomer
- Proper study of shape coexistence in PGCM
  - Shape coexistence but weak mixing

Nuclei with stronger signature ?

Shape coexistence effects in ^{28}Si

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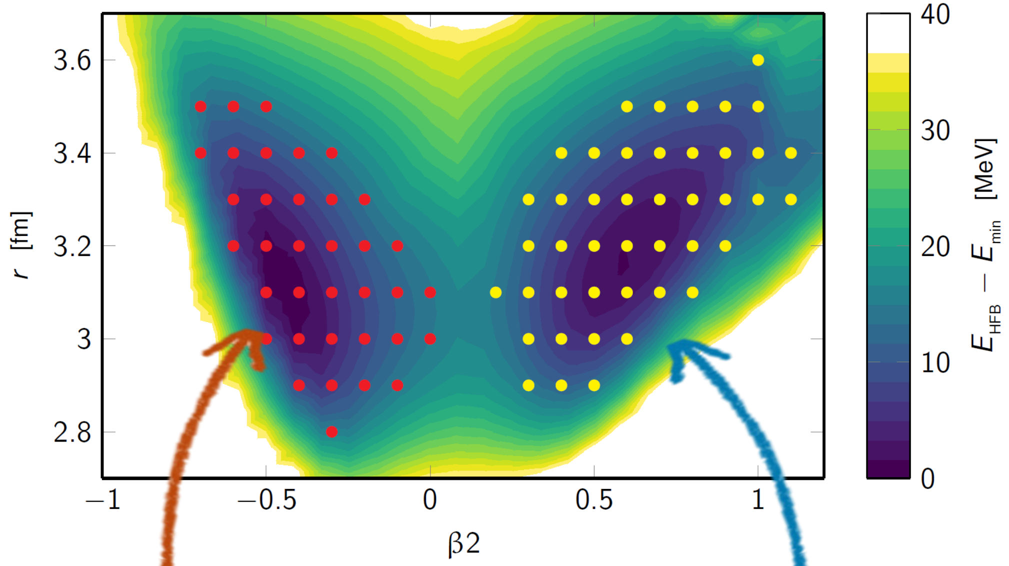

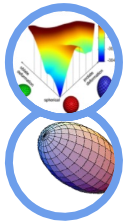

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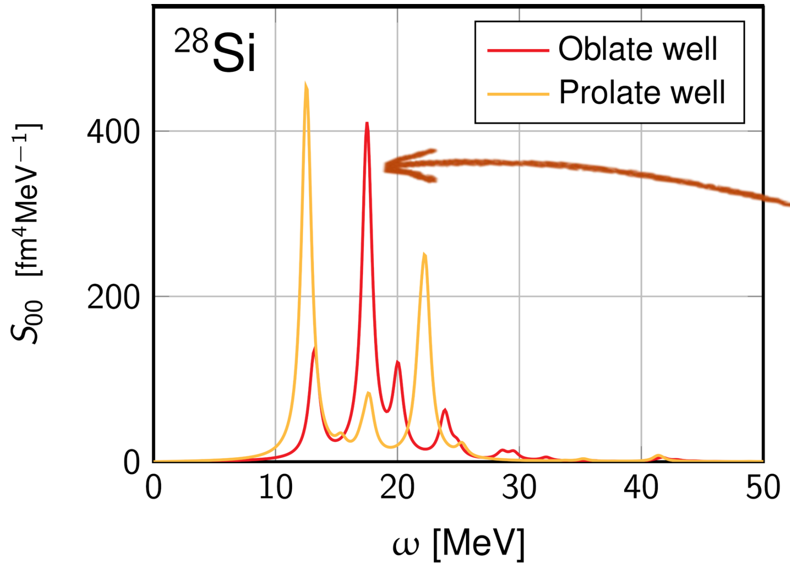

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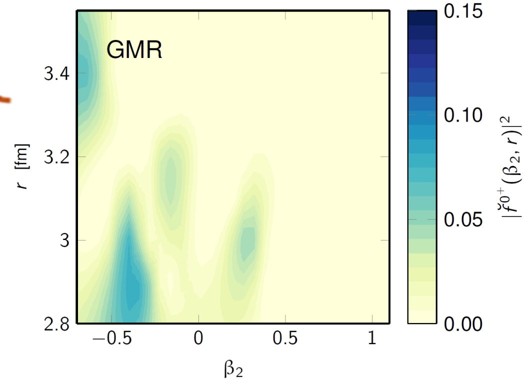

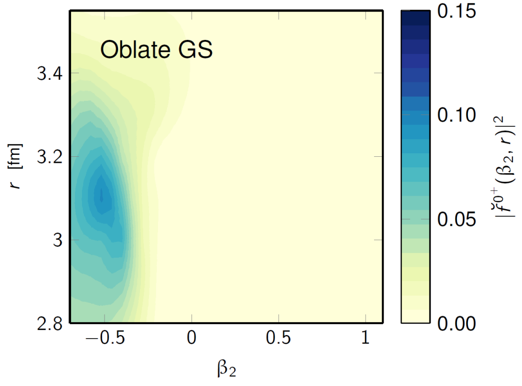

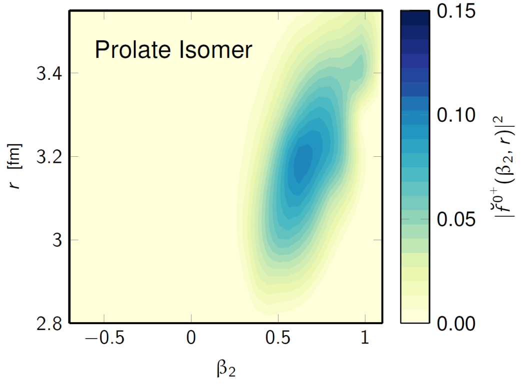

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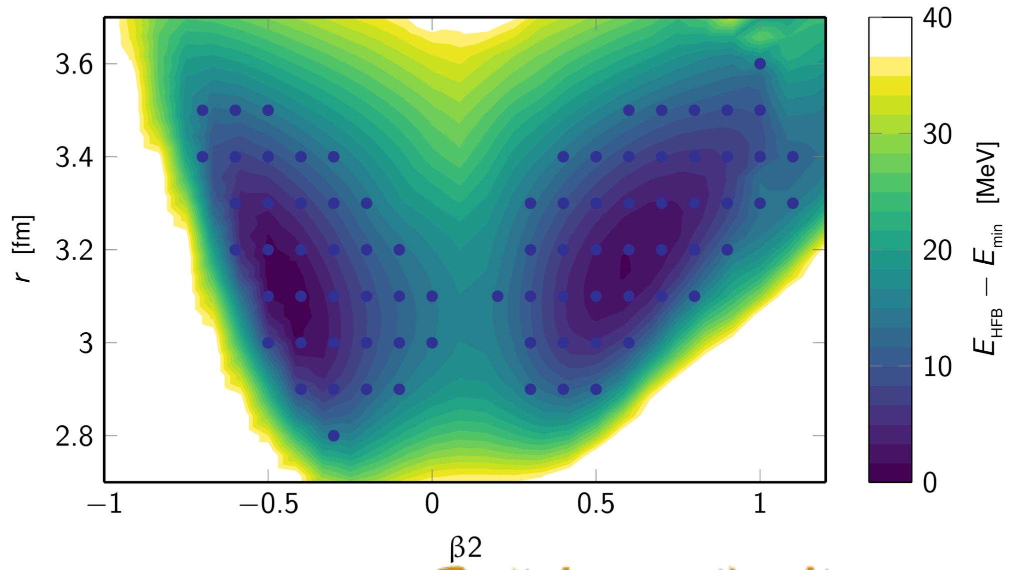
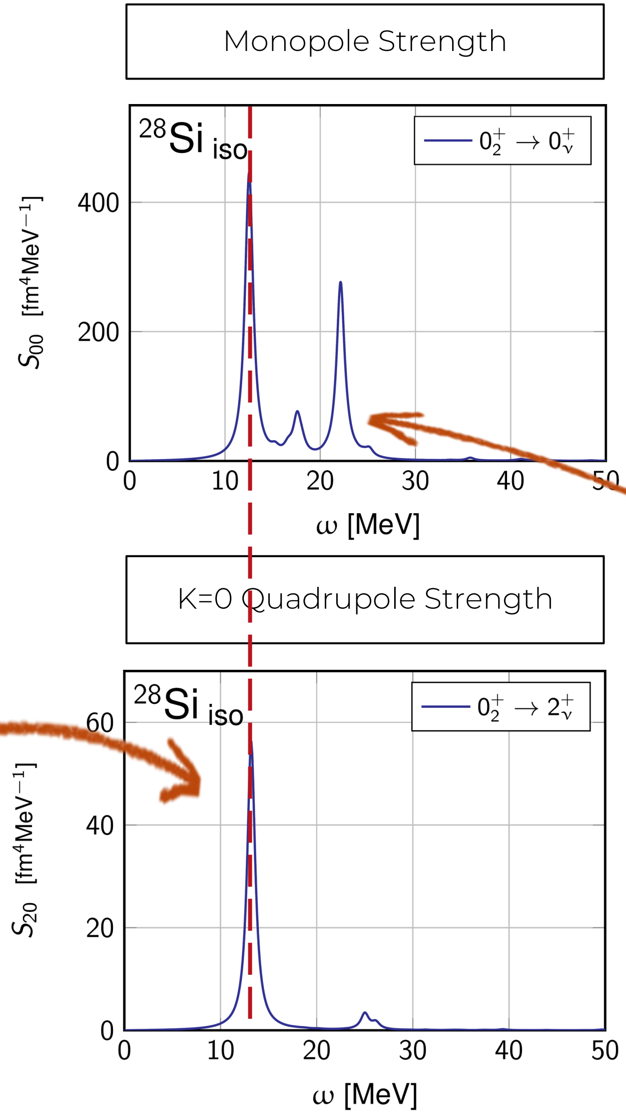
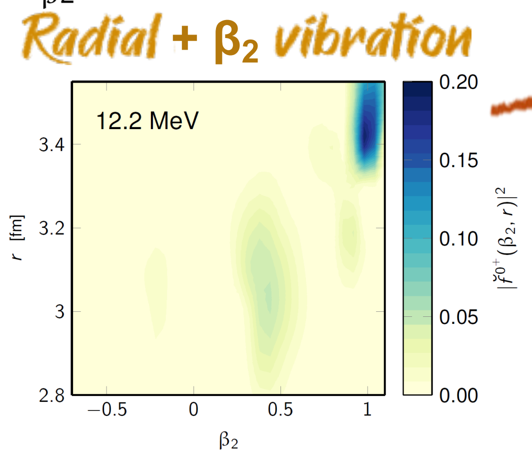
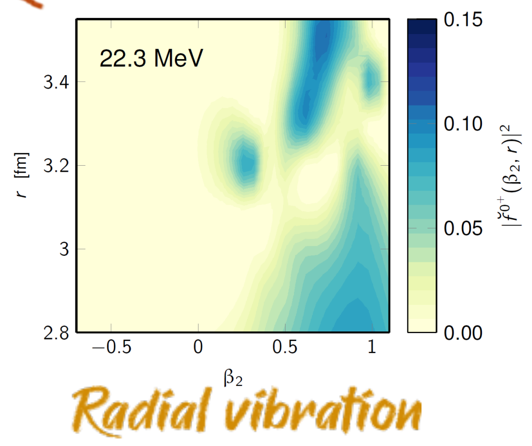


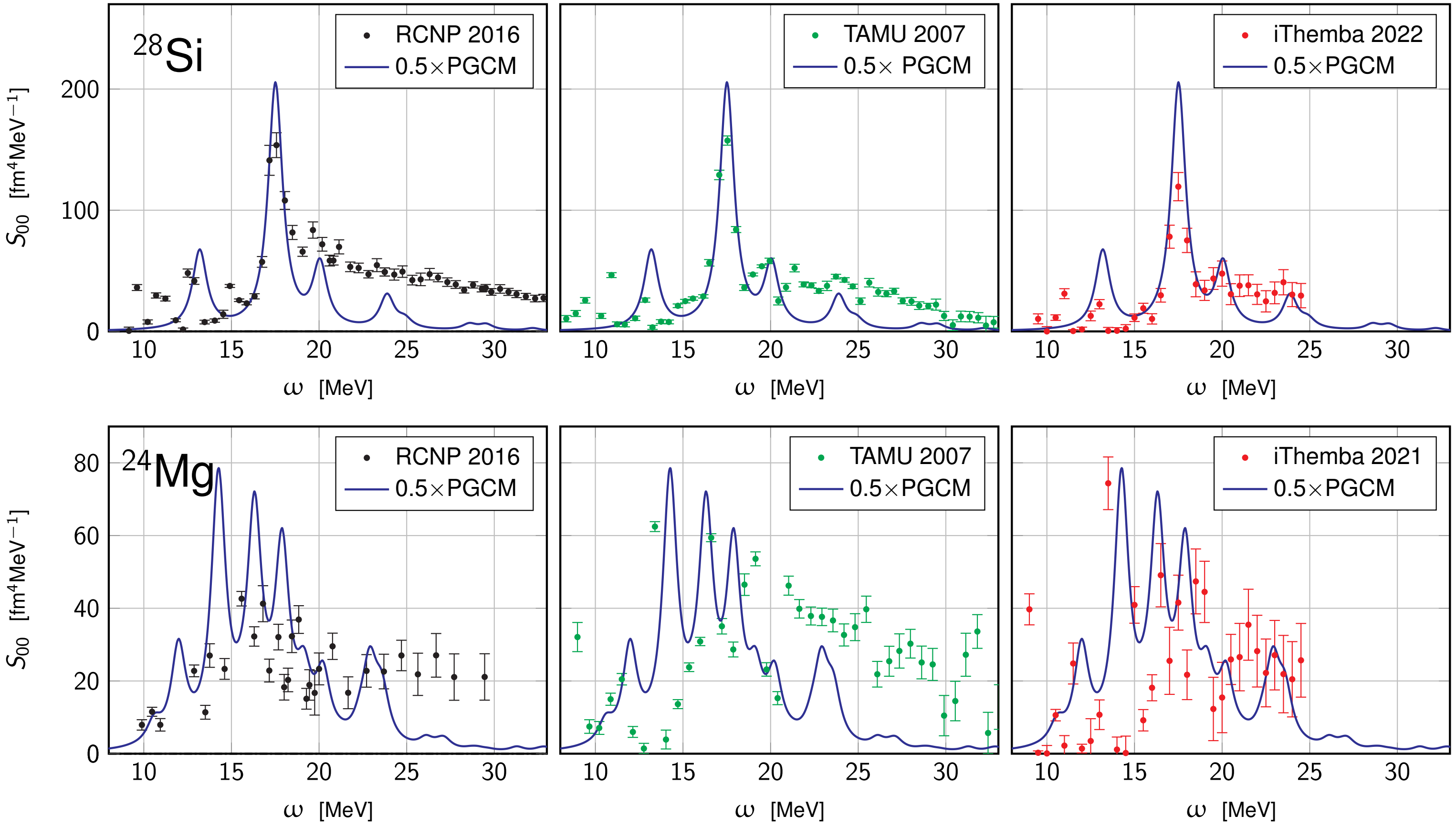






- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

Comparison to experimental data



Ab initio PGCM comparison to experimental data

- Better description of the **main resonance** and **fragmentation**

Experimental data are useful and promising to test different many-body methods

Data are not unambiguous, i.e. higher resolution would be beneficial

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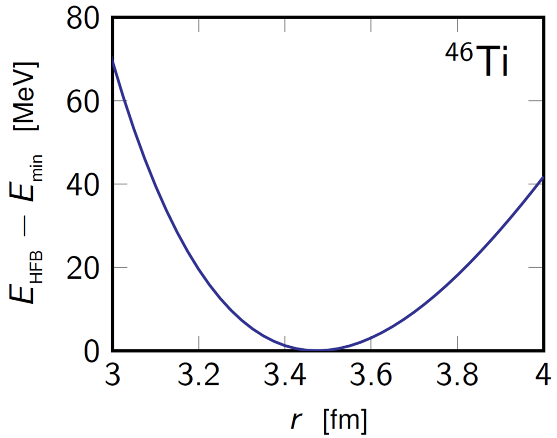
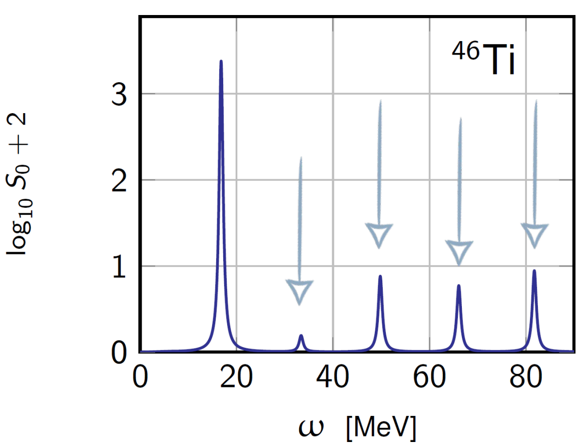
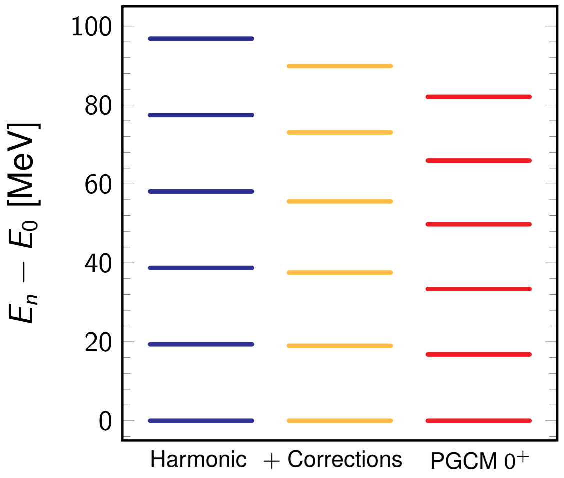
Multi-phonon states in ^{46}Ti

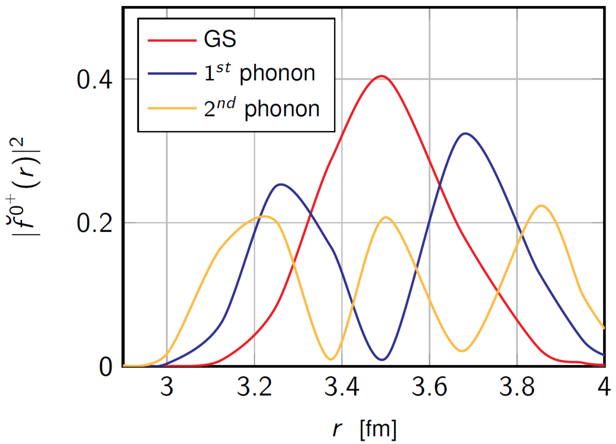
One-dimensional PGCM calculation



- PGCM predicts high-lying states
- Close to the harmonic oscillator eigen-solutions

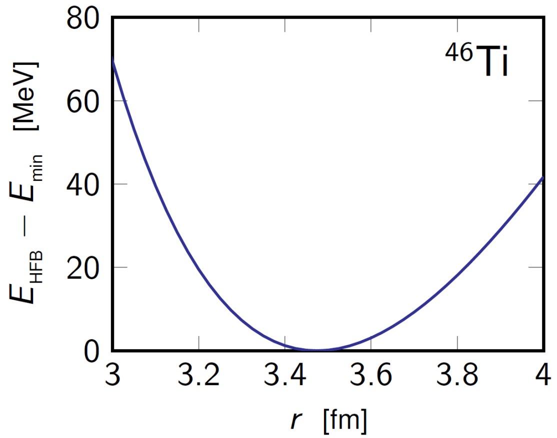






Multi-phonon states in ^{46}Ti

One-dimensional PGCM calculation



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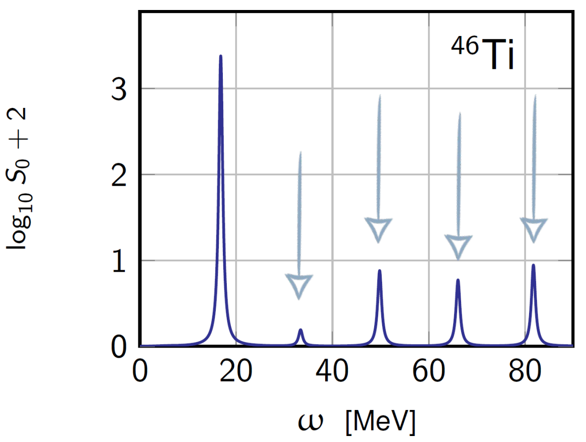
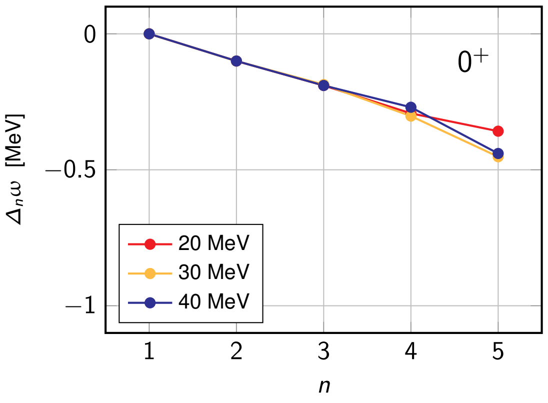
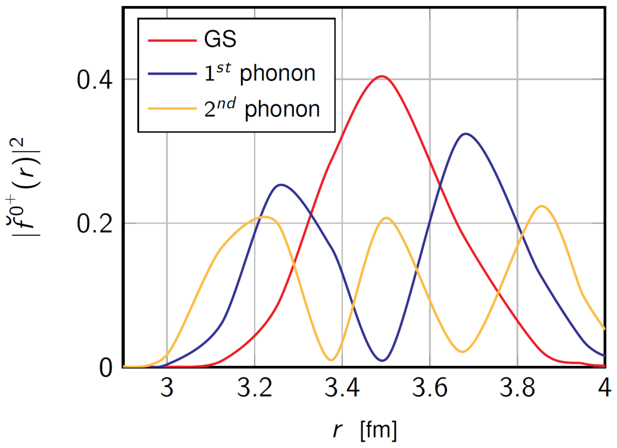




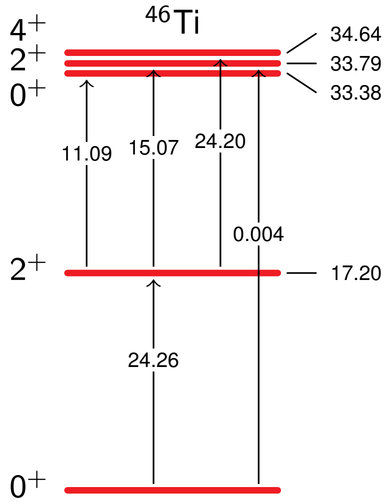


Multi-phonon states in ^{46}Ti

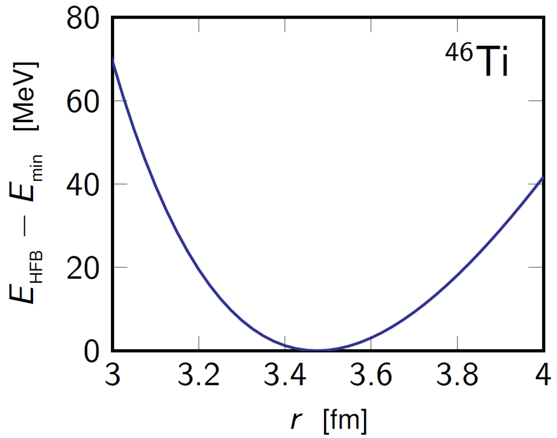
One-dimensional PGCM calculation

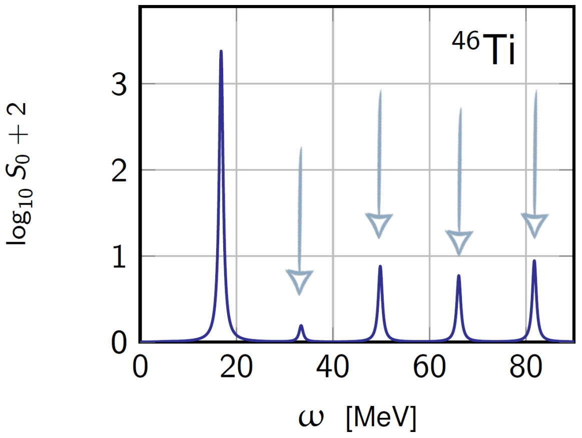
- PGCM predicts high-lying states
- Close to the harmonic oscillator eigen-solutions
- Transitions maximised between neighbouring phonons

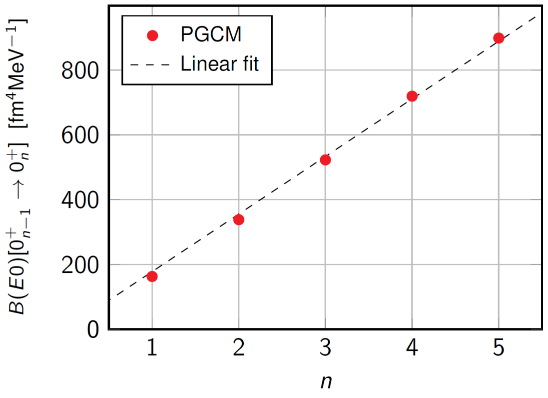
x Linear trend in the transition strength



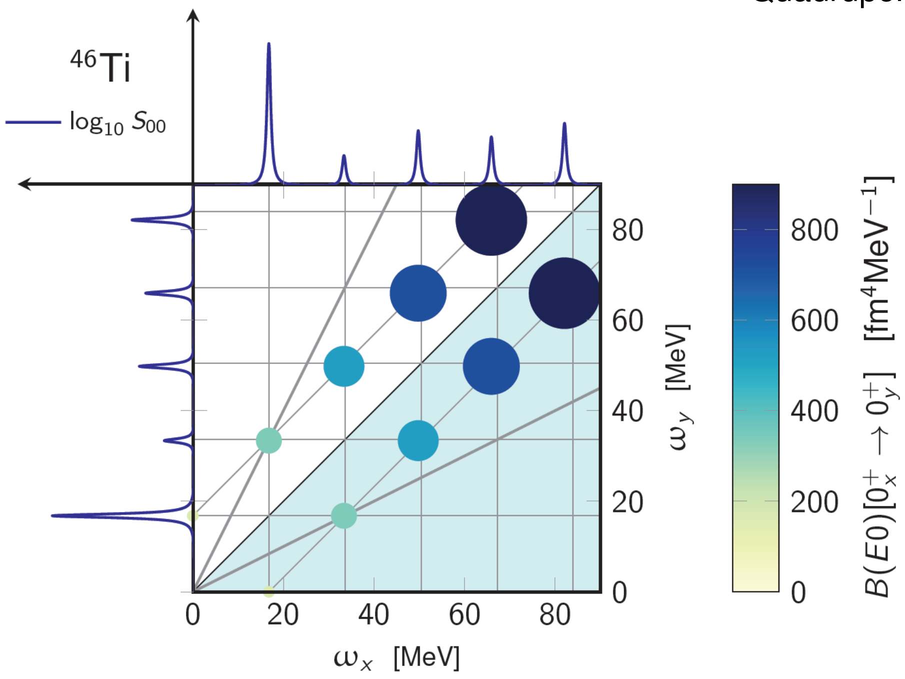
Quadrupole Vibrations



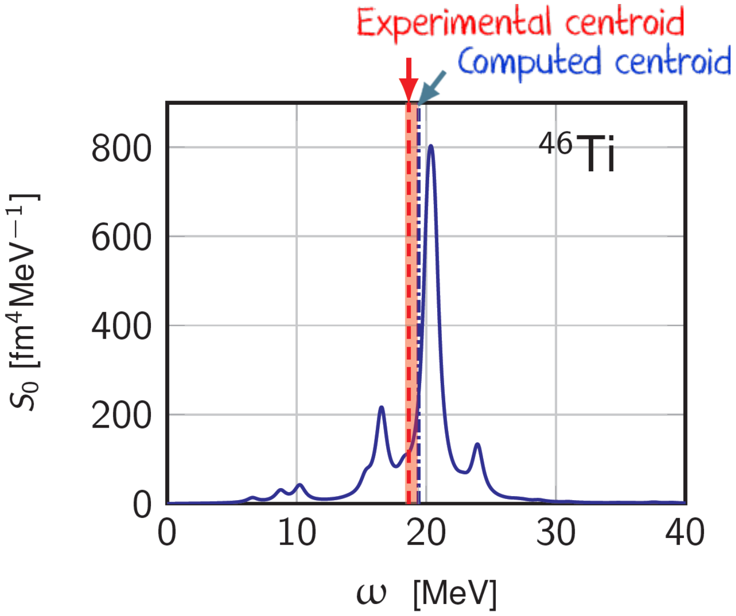


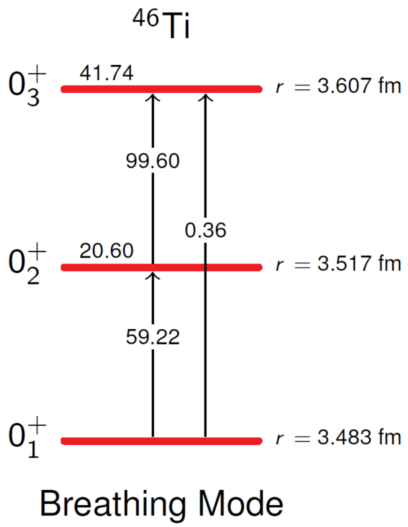


$$|\langle n-1|r^2|n\rangle|^2 = \frac{\hbar}{2m\omega}n$$

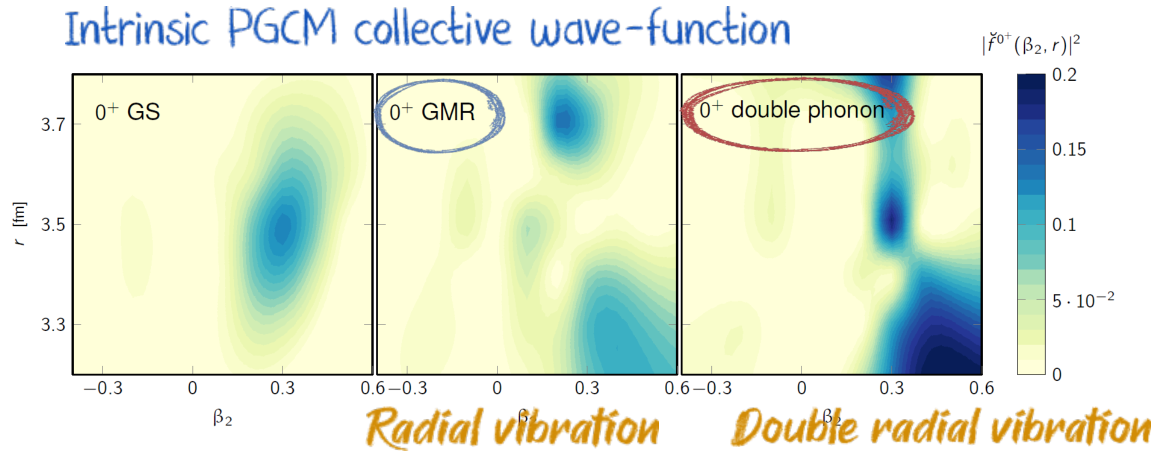


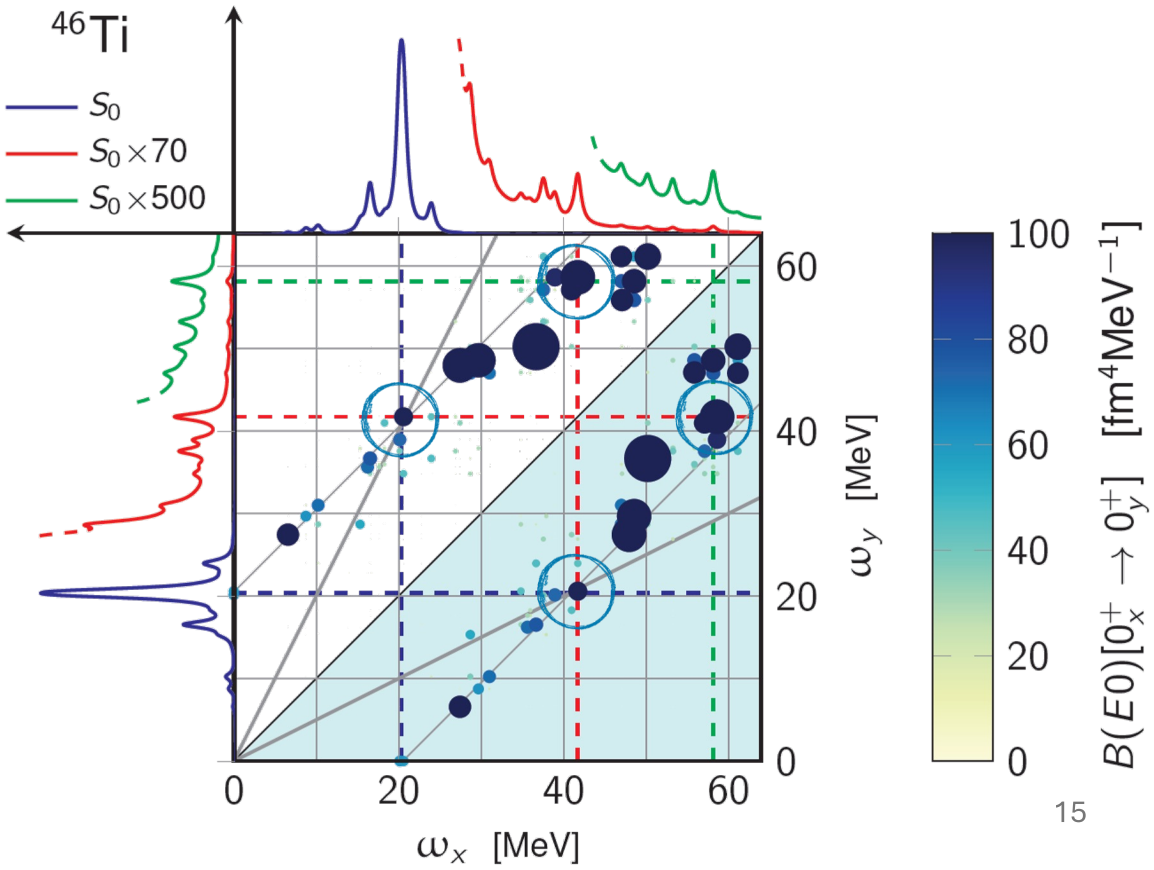
Two-dimensional calculations





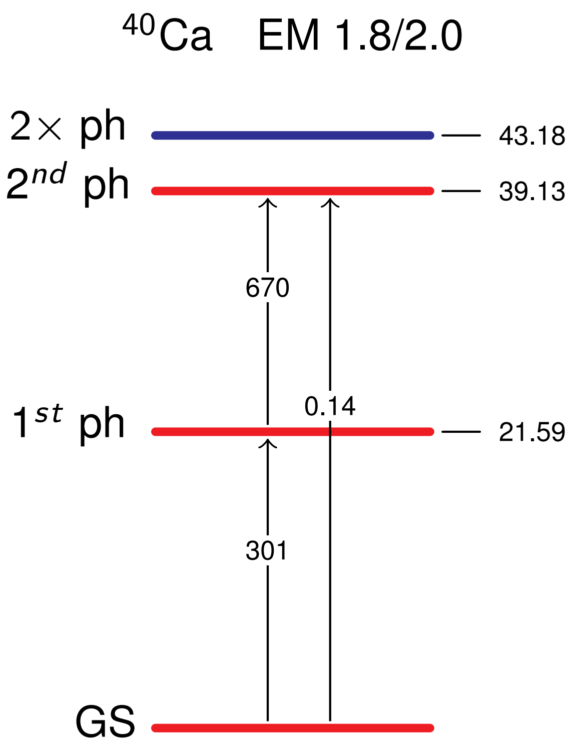
- 2-D PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed
- Harmonicity well confirmed

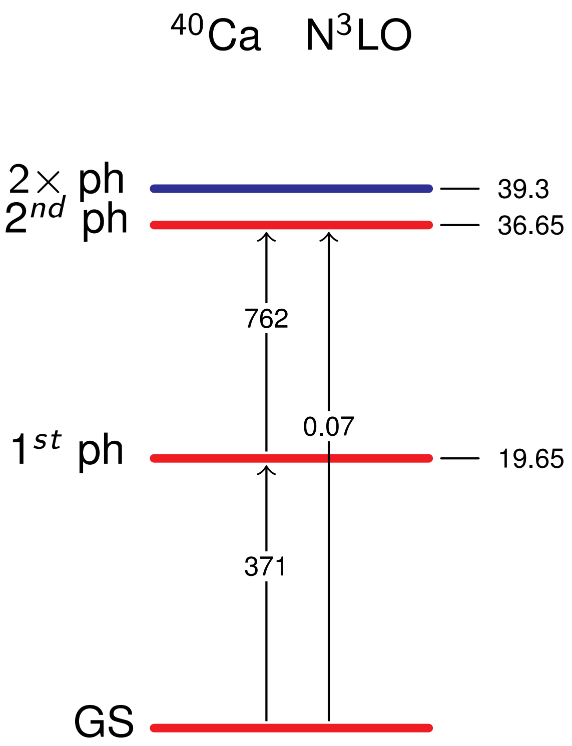




Two-phonon states in ^{40}Ca - preliminary

One-dimensional ab initio GCM calculations





EXP

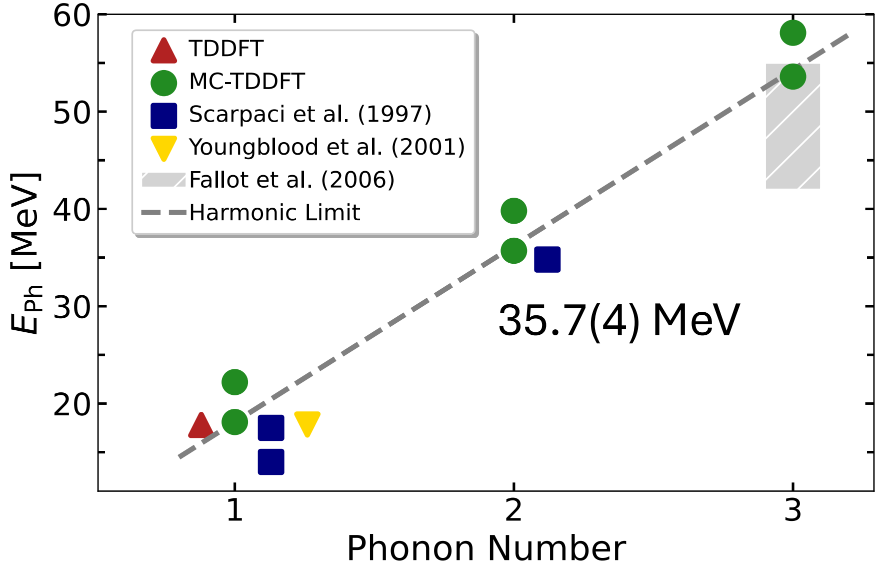
Scarpaci et al, PRC, 56(6), 3187 (1997)

34.8(5) MeV

~ 18 MeV

Theory (TD-DFT)

Marevic et al, PRC, 108, 014620 (2023)



- Preliminary results also predict two- and possibly higher-phonon states
- Small deviations from the harmonic picture
- More detailed study following

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Ab initio PGCM as a tool for GRs study

- Shape isomerism effects on GRs Physics

PGCM naturally predicts multi-phonon states

- Multi-phonon states in the monopole channel
- Better probe for the compressibility ?
- Preliminary quadrupole results
- Small deviations from the harmonic picture
- Tensions with the Brink-Axel hypothesis ?

2^{nd}-RPA possible ? [Minato, arXiv:2411.01709 (2024)]