Microscopic Description of Quantum Phase Transitions in Nuclei

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Peter Ring

Technical University Munich

TECHNISCHE UNIVERSITÄT MÜNCHEN

TUM LMU Excellence Cluster Universe

MLL

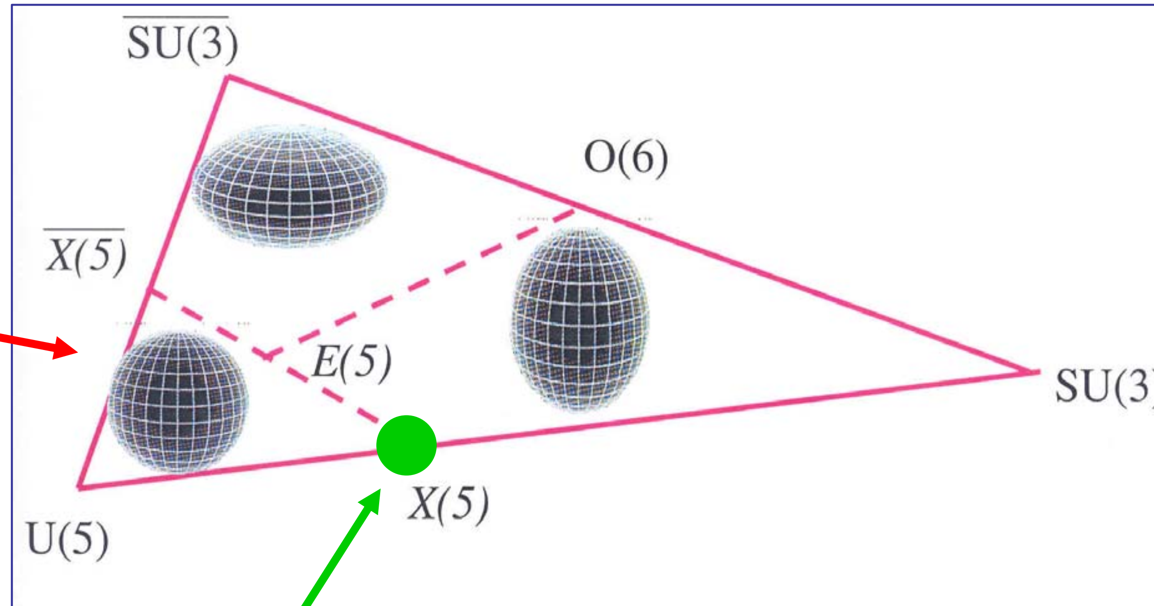
Content:

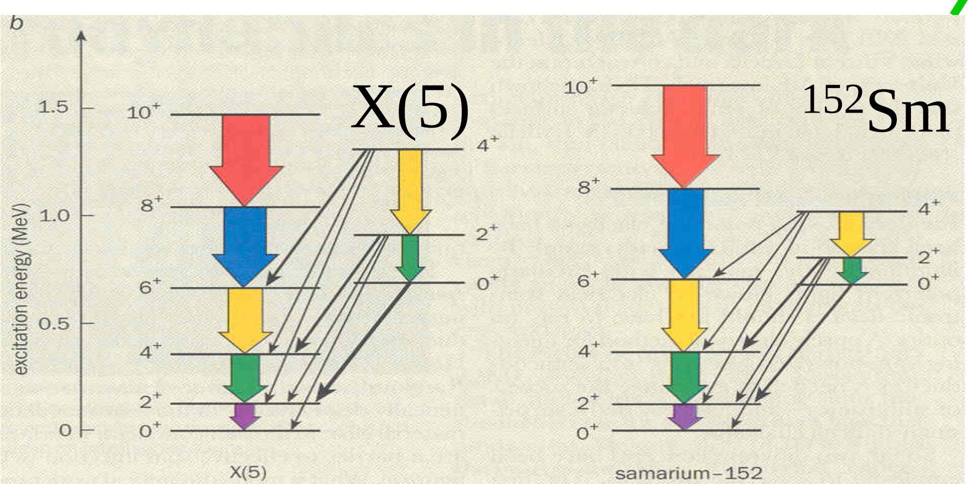
- Quantum phase transitions
- Covariant density functional theory
- Calculations of Spectra
  - Generator Coordinate Method
  - axial symmetric calculations of the Ne-chain
  - 5-dimensional Bohr Hamiltonian
- Order parameters
  - R42, B(E2),
  - isomer shifts,
  - E0-strength
- Conclusions

Quantum phase transitions and critical symmetries

Interacting Boson Model

Casten Triangle



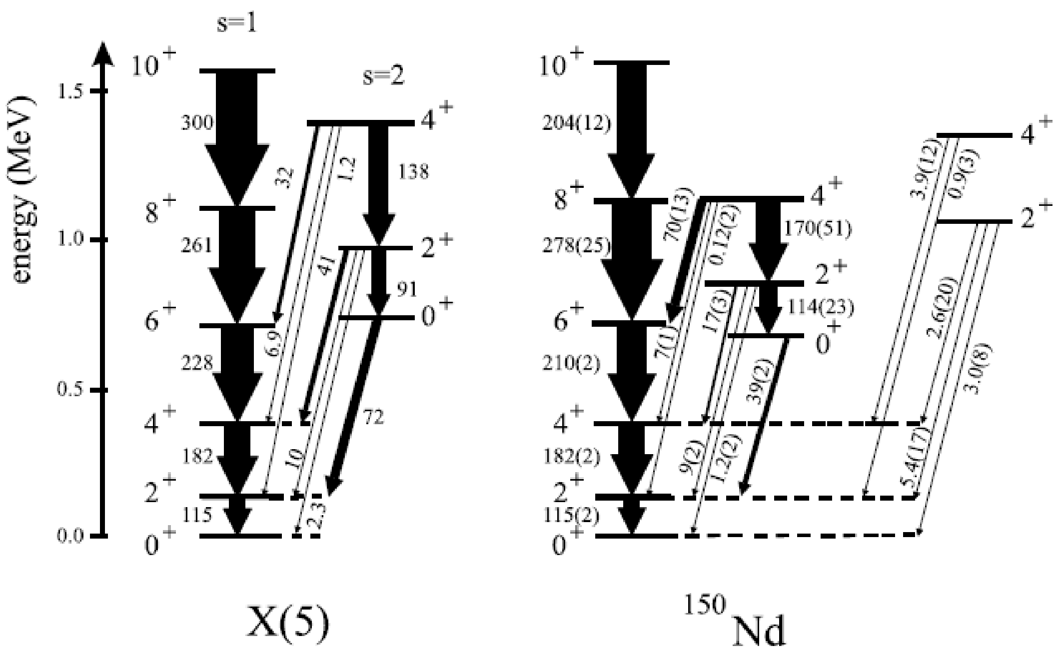


E(5): F. Iachello, PRL 85, 3580 (2000)
X(5): F. Iachello, PRL 87, 52502 (2001)

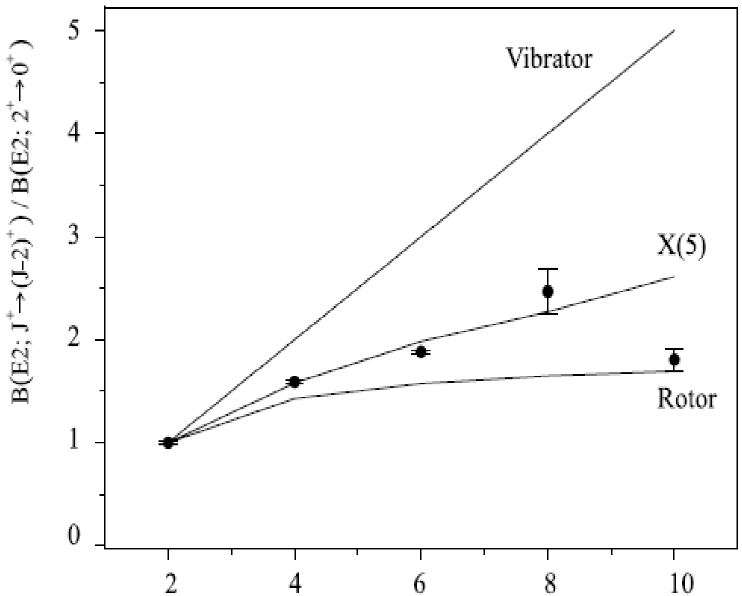
R.F. Casten, V. Zamfir, PRL 85 3584, (2000)

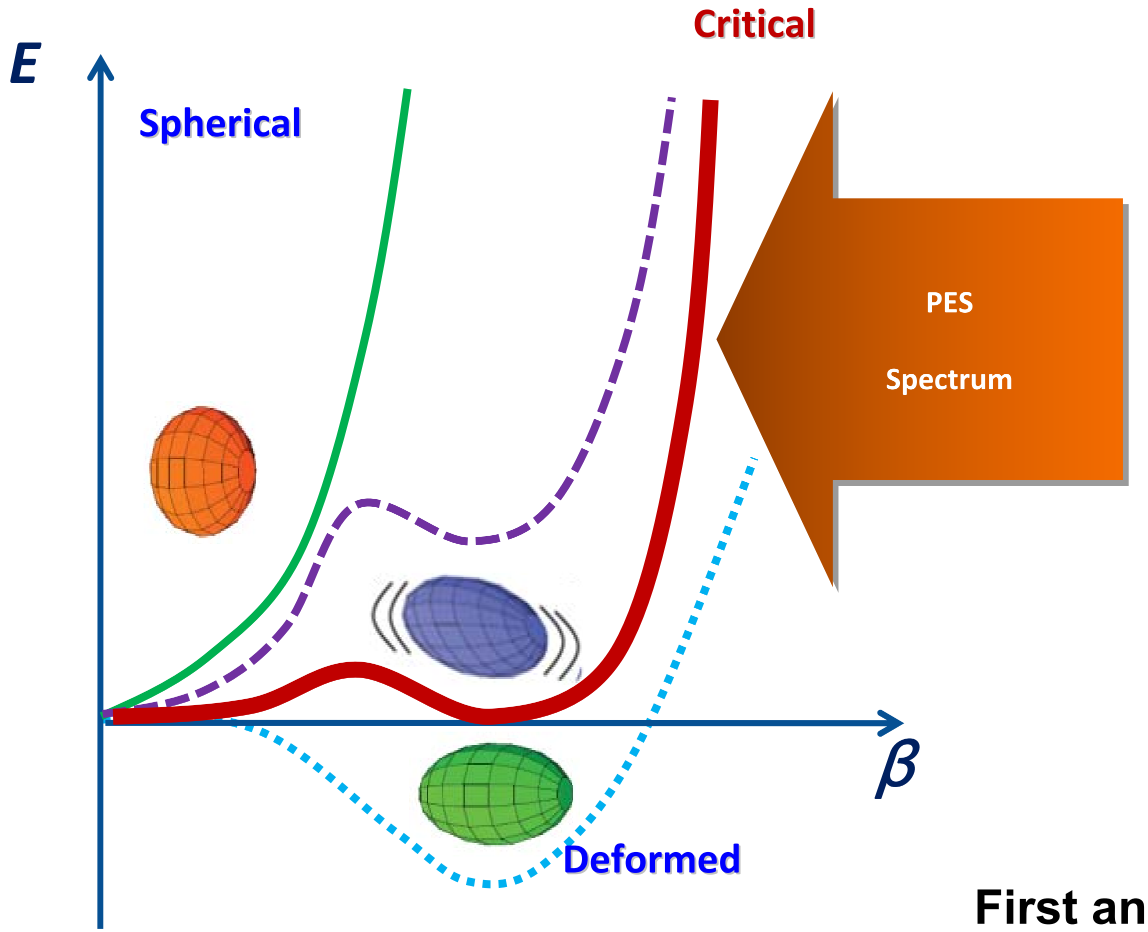
Transition U(5) → SU(3) in Nd-isotopes

R. Krücken *et al*, PRL 88, 232501 (2002)



R = BE2(J→J-2) / BE2(2→0)





First and second order QPT can occur between systems characterized by different ground-state **shapes**.

Control Parameter: **Number of nucleons**

Density functional theory in nuclei:

$$E[\hat{\rho}] = \langle \Psi | H | \Psi \rangle \approx \langle \Phi | H_{eff}(\rho) | \Phi \rangle$$

Skyrme
Gogny
RMF

$|\Phi\rangle$ Slater determinant $\Longleftrightarrow$ $\hat{\rho}$ density matrix

$$|\Phi\rangle = \mathcal{A}\{\varphi_1(\mathbf{r}_1)\ldots\varphi_(\mathbf{r}_\mathbf{A})\} \Longleftrightarrow \hat{\rho}(\mathbf{r},\mathbf{r}') = \sum_{i=1}^{A} |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r}')|$$

Mean field:

$$\hat{h} = \frac{\delta E}{\delta \hat{\rho}}$$

Eigenfunctions:

$$\hat{h}|\varphi_i\rangle = \varepsilon_i |\varphi_i\rangle$$

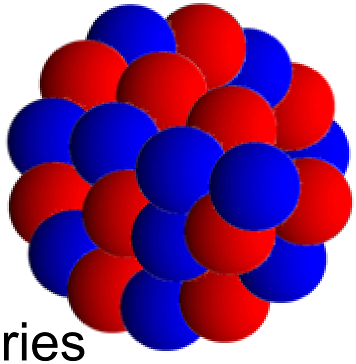
Interaction:

$$\hat{V} = \frac{\delta^2 E}{\delta\hat{\rho}\delta\hat{\rho}}$$

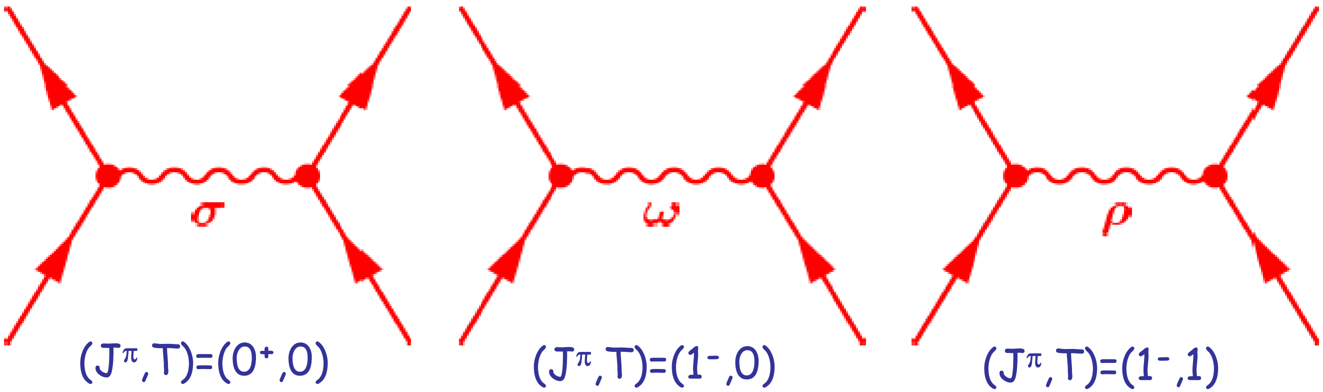
Extensions: Pairing correlations, Covariance
Relativistic Hartree Bogoliubov (RHB) theory

$$E[\rho]$$

Walecka model:



- the basis is an effective Lagrangian with all relativistic symmetries
- it is used in a mean field concept (Hartree-level)
- with the no-sea approximation



$$S(\mathbf{r}) = g_\sigma \sigma(\mathbf{r}) \qquad V(\mathbf{r}) = g_\omega \omega(\mathbf{r}) + g_\rho \vec{\tau}\vec{\rho}(\mathbf{r}) + eA(\mathbf{r})$$

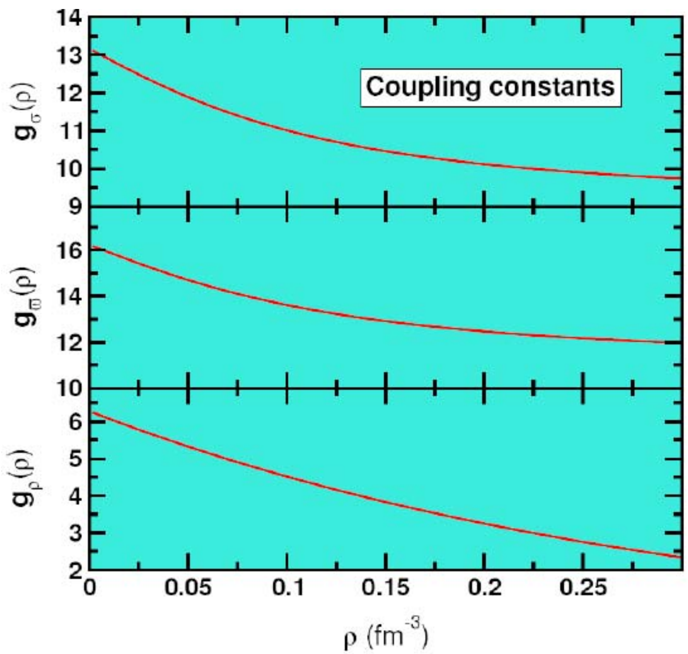
Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

Rho-meson: isovector field

Effective density dependence:

The basic idea comes from ab initio calculations
density dependent coupling constants include Brueckner correlations
and threebody forces



non-linear meson coupling: **NL3**

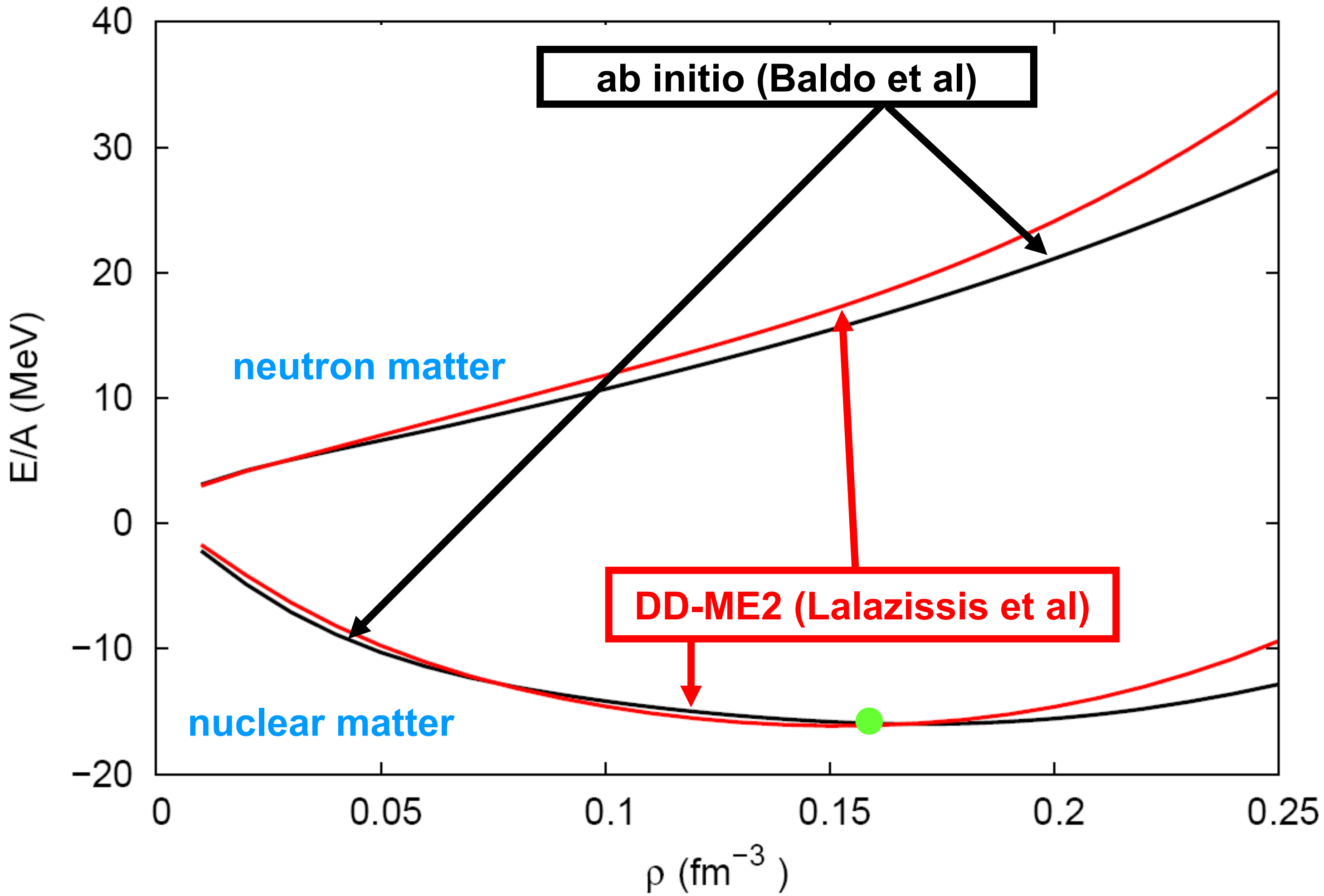
Point-coupling models
with derivative terms:

$g_\sigma(\rho)$ $g_\omega(\rho)$ $g_\rho(\rho)$

adjusted to ground state properties of finite nuclei

Manakos and Mannel, Z.Phys. **330**, 223 (1988)
Bürvenich, Madland, Maruhn, Reinhard, PRC **65**, 044308 (2002): **PC-F1**
Niksic, Vretenar, P.R., PRC 78, 034318 (2008): **DD-PC1**

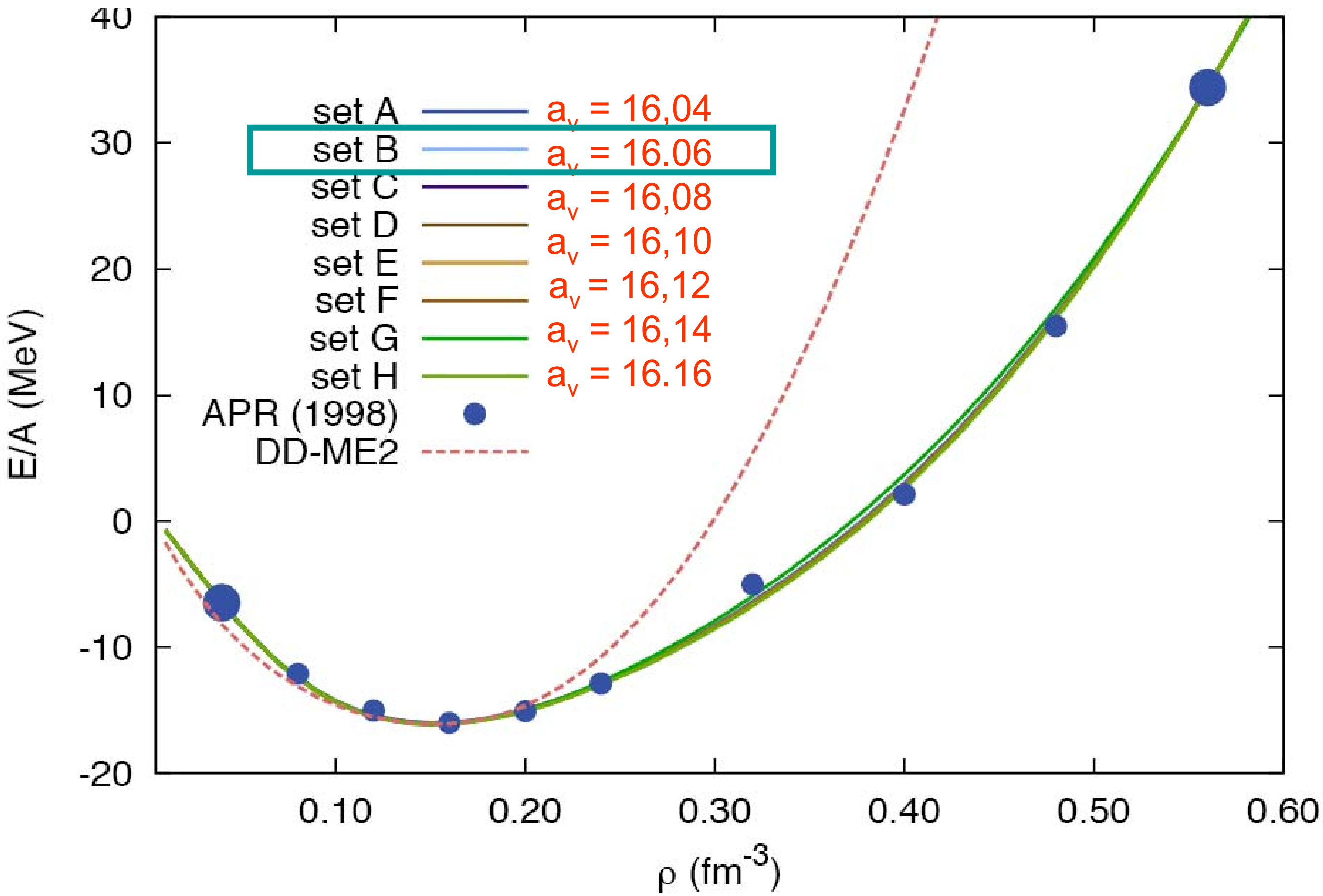
Comparision with ab-initio calculations:



we find excellent agreement with ab initio calculations of Baldo et al.

Adjustment to ab-initio calculations:

point coupling model is adjusted to microscopic nuclear matter:

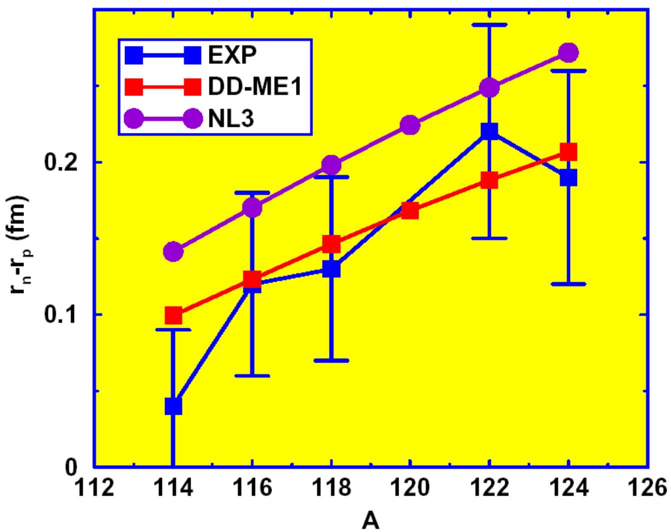


ρ_{sat} = 0.152 fm^{-3}
m^* = 0.58m
K_{nm} = 230 MeV

DD-PC1

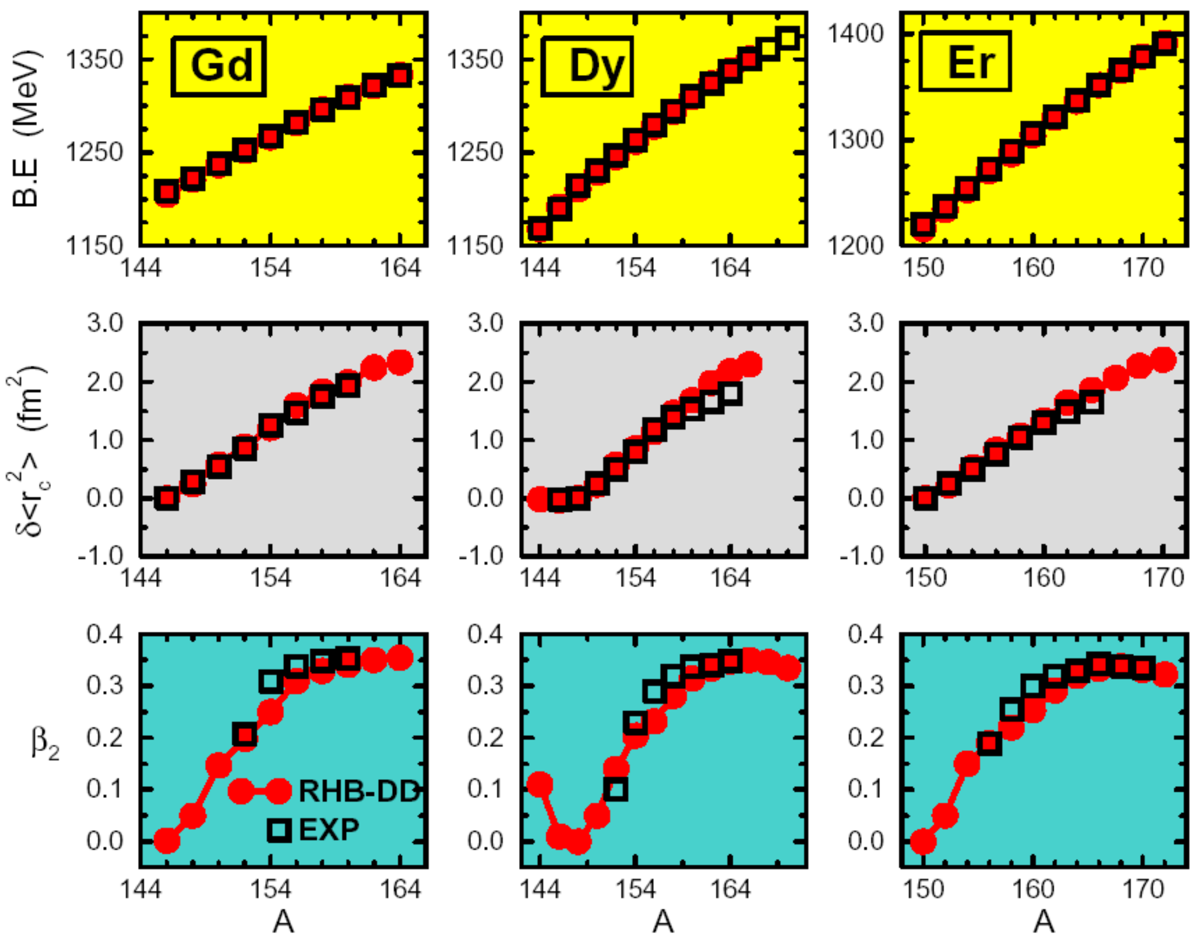
A. Akmal, V.R. Pandharipande, and D.G. Ravenhall, PRC. 58, 1804 (1998).

Ground state properties of finite nuclei:

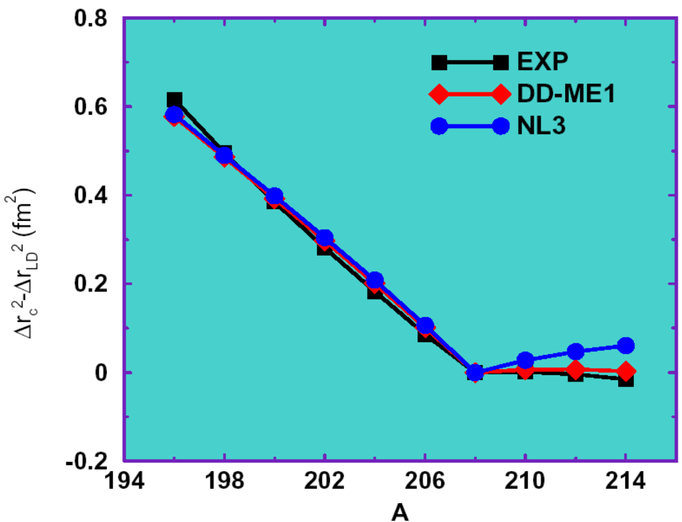


DD-ME1

Binding energies, charge isotope shifts, and quadrupole Deformations of Gd, Dy, and Er isotopes.

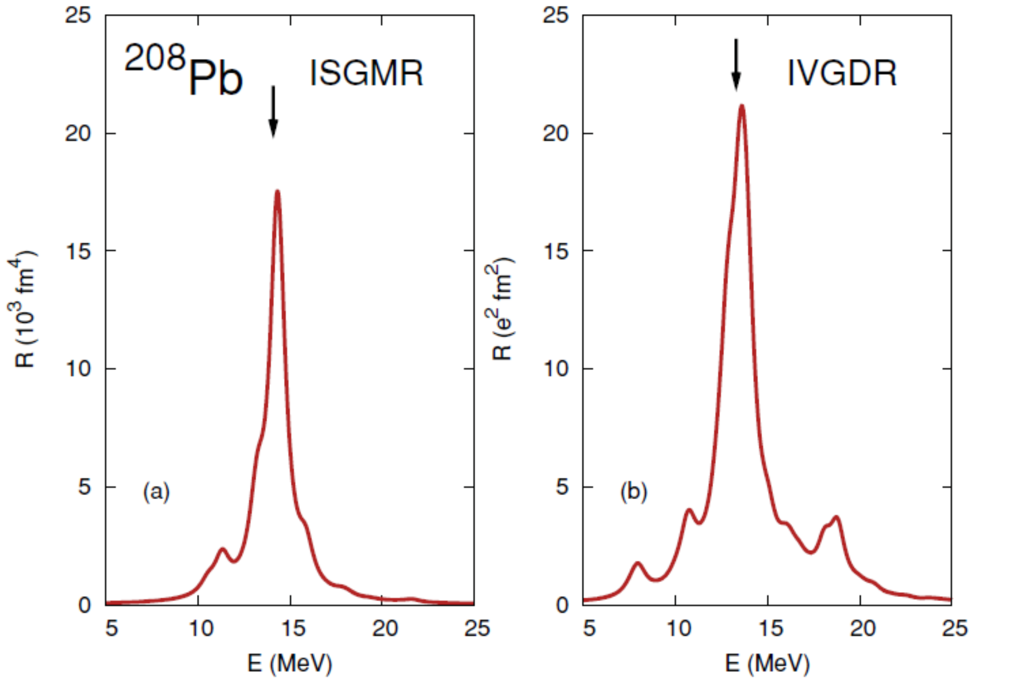


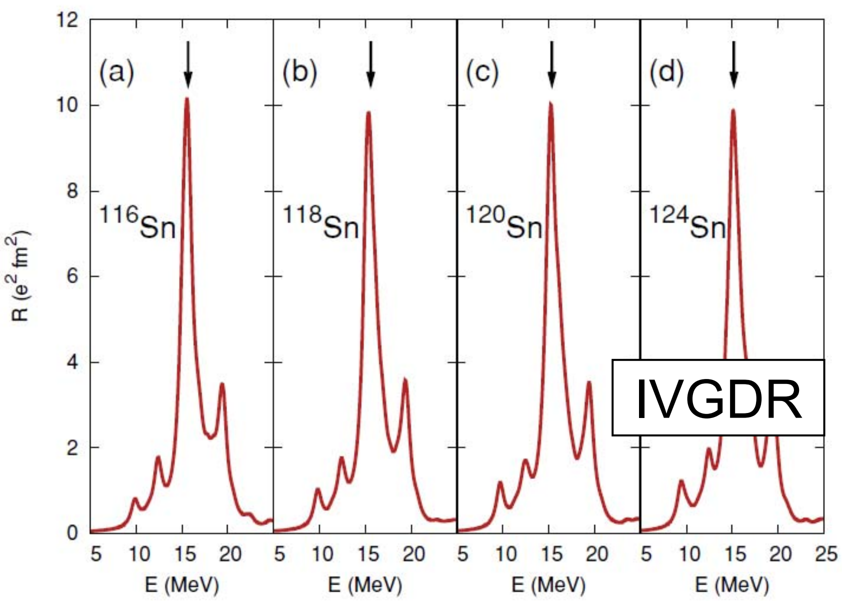
Charge isotope shifts in even-A Pb isotopes.



DD-PC1
Giant resonances:

T. Niksic et al, (2008)





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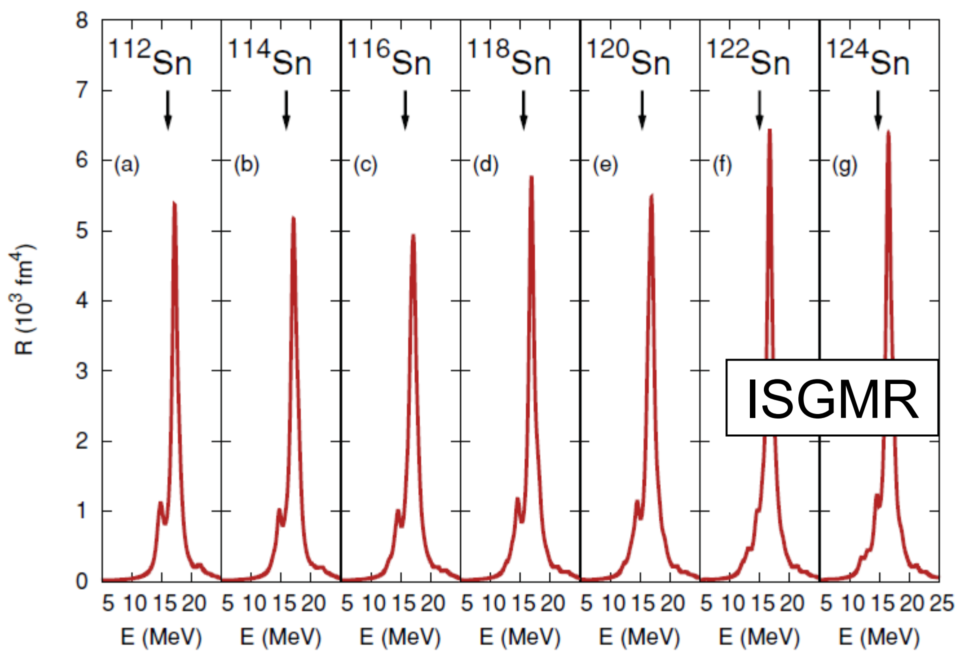


Can a universal density functional, adjusted to ground state properties, at the same time reproduce critical phenomena in spectra ?

We need a method to derive spectra:

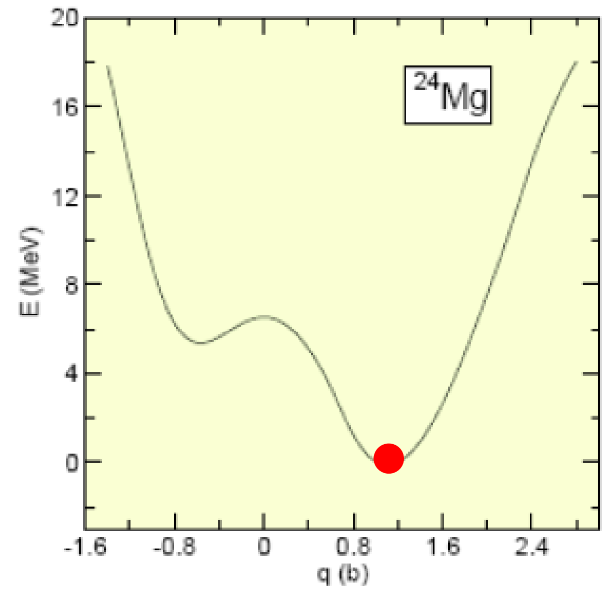
Generator coordinate method (GCM),

Adiabatic time-dependent relativistic mean field (ATDRMF)

We consider the chain of Ne-isotopes with a phase transition from spherical (U(5)) to axially deformed (SU(3))

The generator coordinate method:

$$\langle \delta\Phi | \hat{H} - q\hat{Q} | \Phi \rangle = 0$$



$$\to \quad | q \rangle = | \Phi(q) \rangle$$

Constraint relativistic mean field produces
wave functions depending on a generator coordinate q

$$|\Psi\rangle = \int dq\, f(q) |q\rangle$$

the GCM wave function is a
superposition of Slater determinants

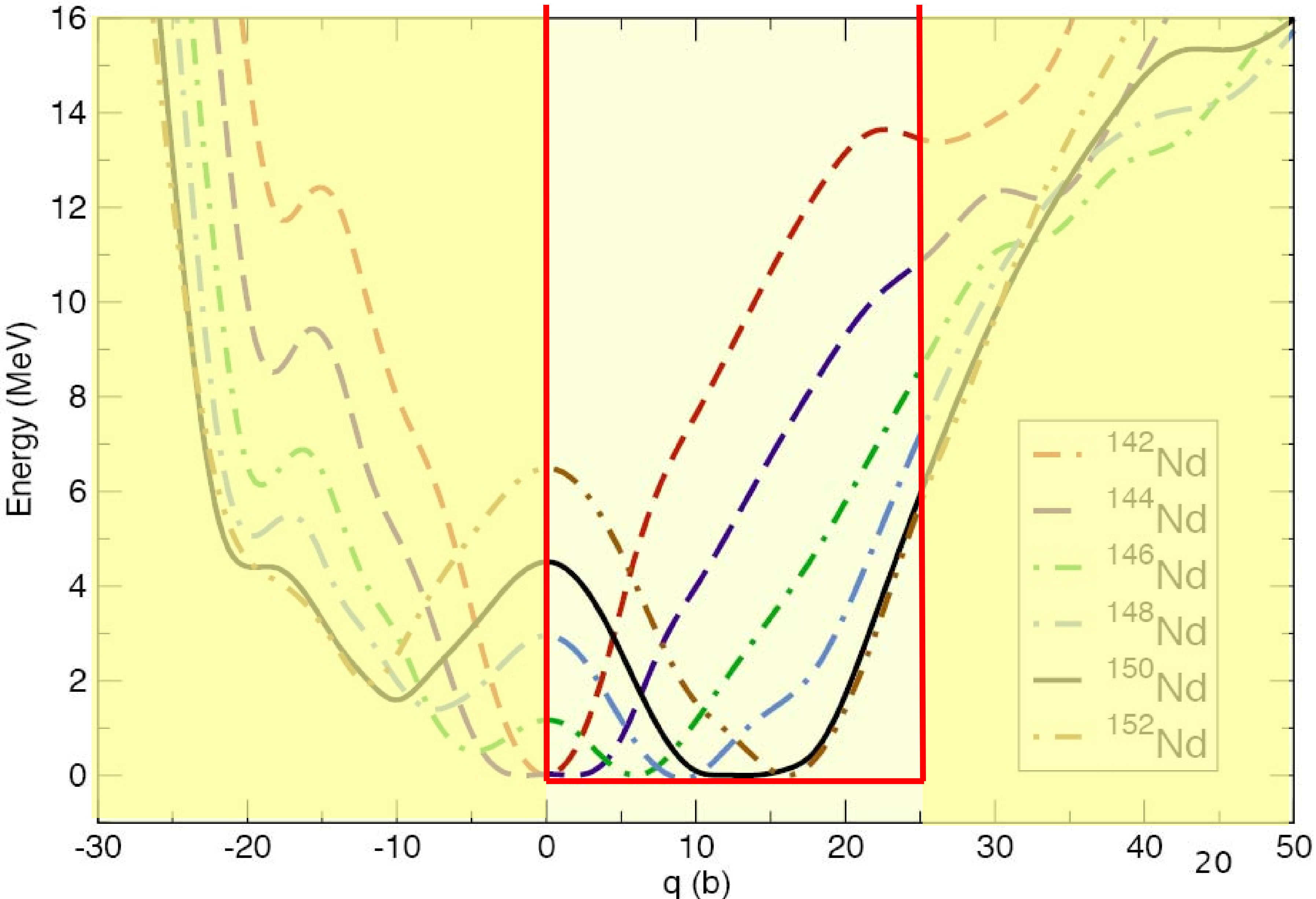
$$\int dq' \left[\langle q|H|q'\rangle - E\langle q|q'\rangle \right] f(q') = 0$$

Hill-Wheeler equation:

$$|\Psi\rangle = \int dq\, f(q) \hat{P}^N \hat{P}^I |q\rangle$$

with projection:

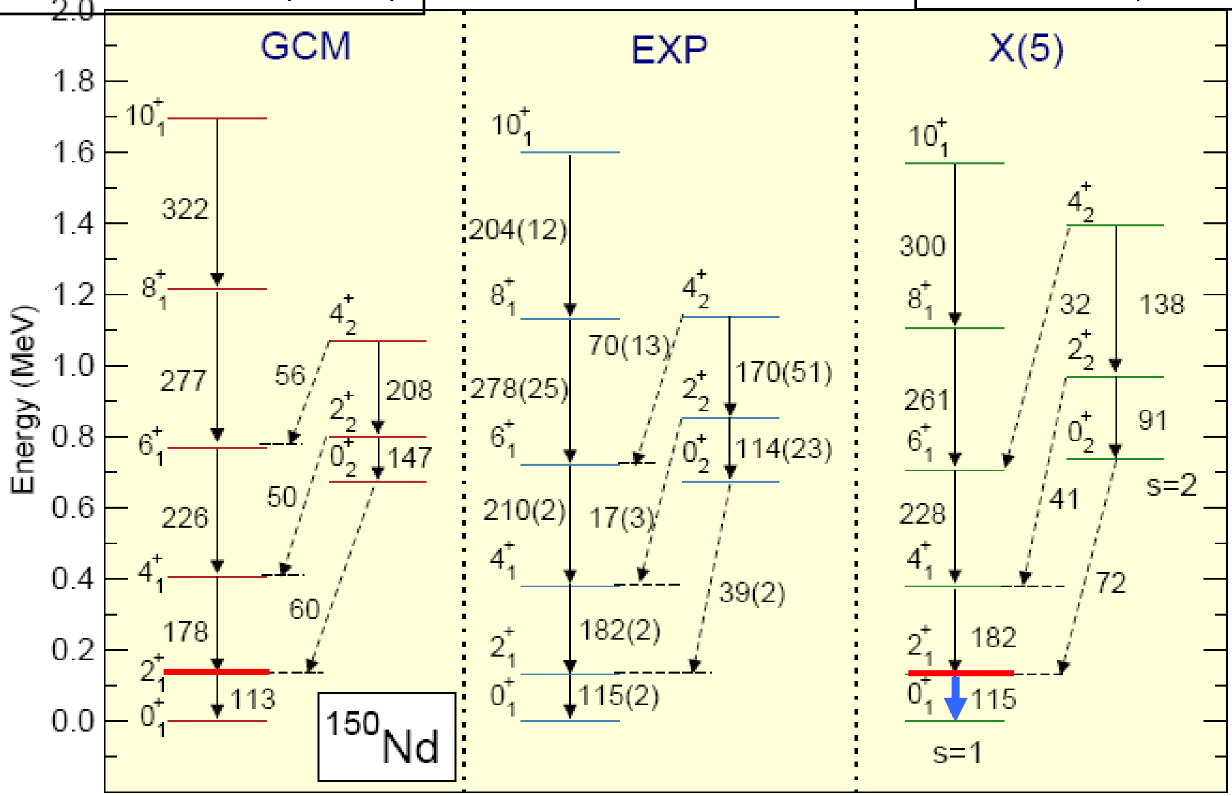
Self-consistent RMF plus Lipkin-Nogami BCS binding energy curves of $^{142-152}Nd$, as functions of the mass quadrupole moment.



R. Krücken *et al*, PRL 88, 232501 (2002)

Niksic *et al* PRL 99, 92502 (2007)

F. Iachello, PRL 87, 52502 (2001)

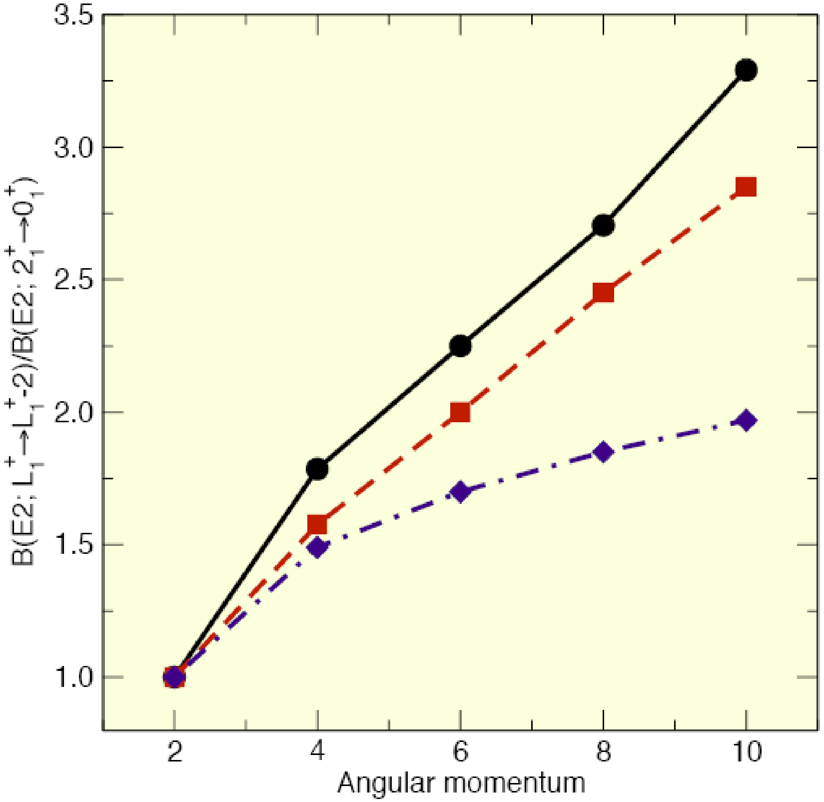


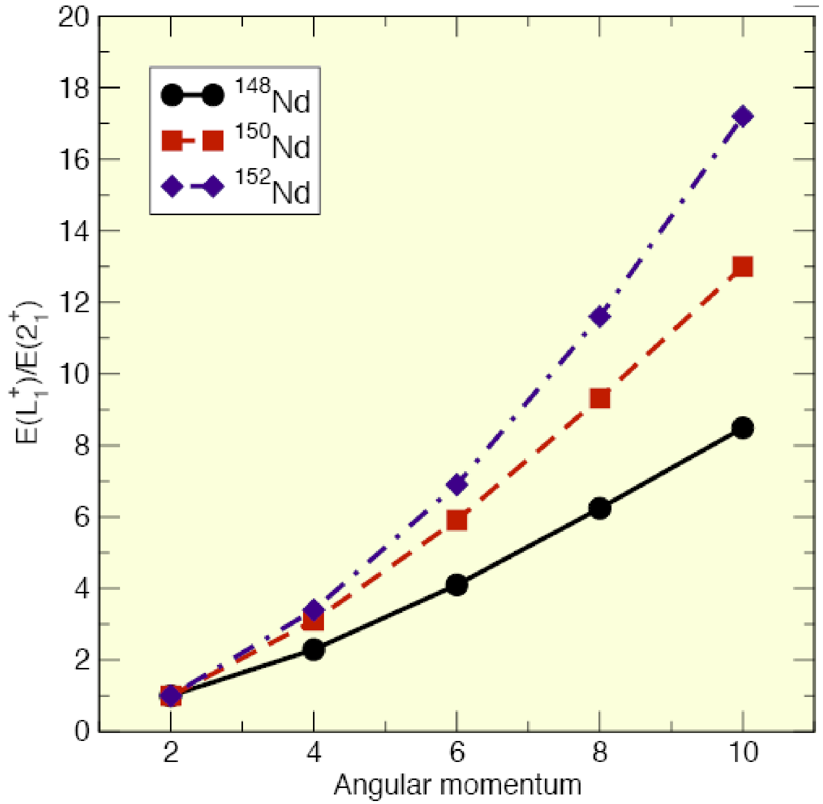
GCM: only one scale parameter: **$E(2_1)$**

X(5): two scale parameters: **$E(2_1)$, $BE2(2_2 \rightarrow 0_1)$**

Problem of GCM at this level: **restricted to γ=0**

B(E2; L → L-2) values and excitation energies for the yrast states: ^{148}**Nd**, ^{150}**Nd**, and ^{152}**Nd**, calculated with the GCM:





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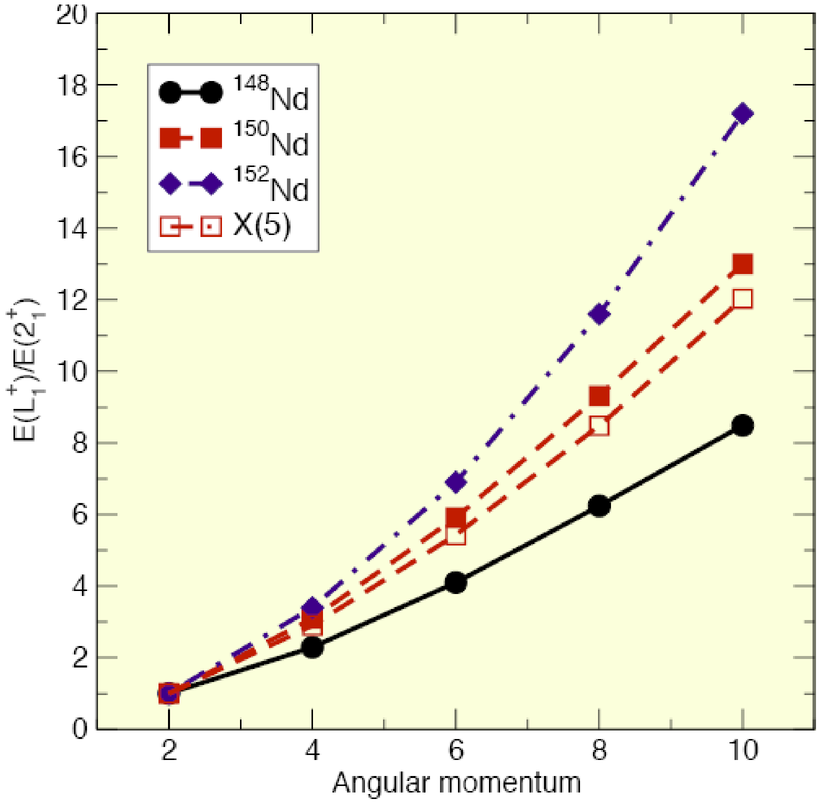
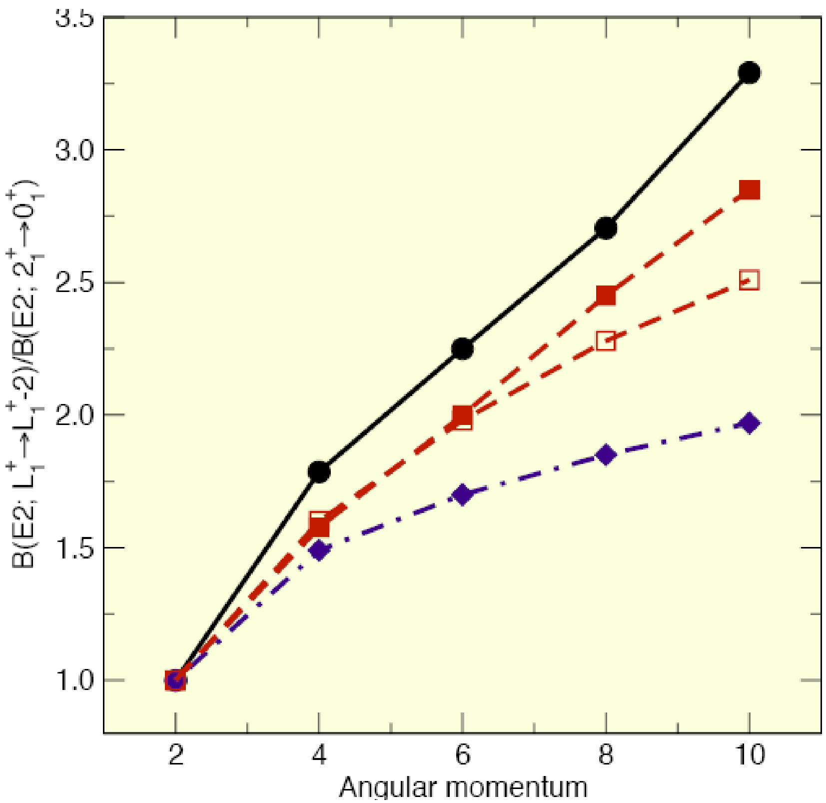
B(E2; L → L-2) values and excitation energies for the yrast states: ^{148}**Nd**, ^{150}**Nd**, and ^{152}**Nd**, calculated with the GCM and compared with those predicted by the **X(5)**:





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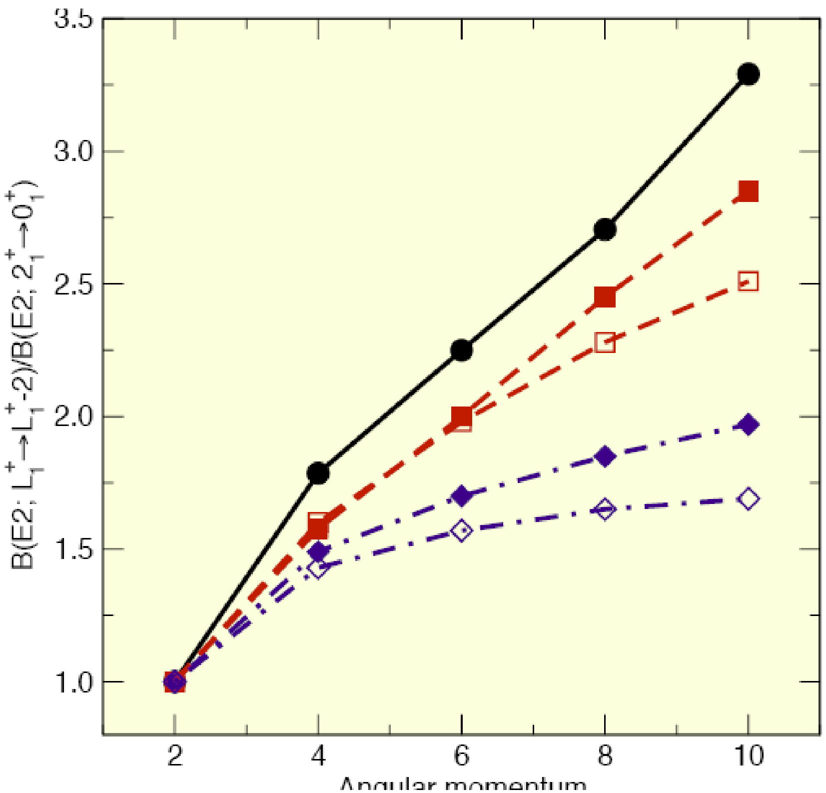
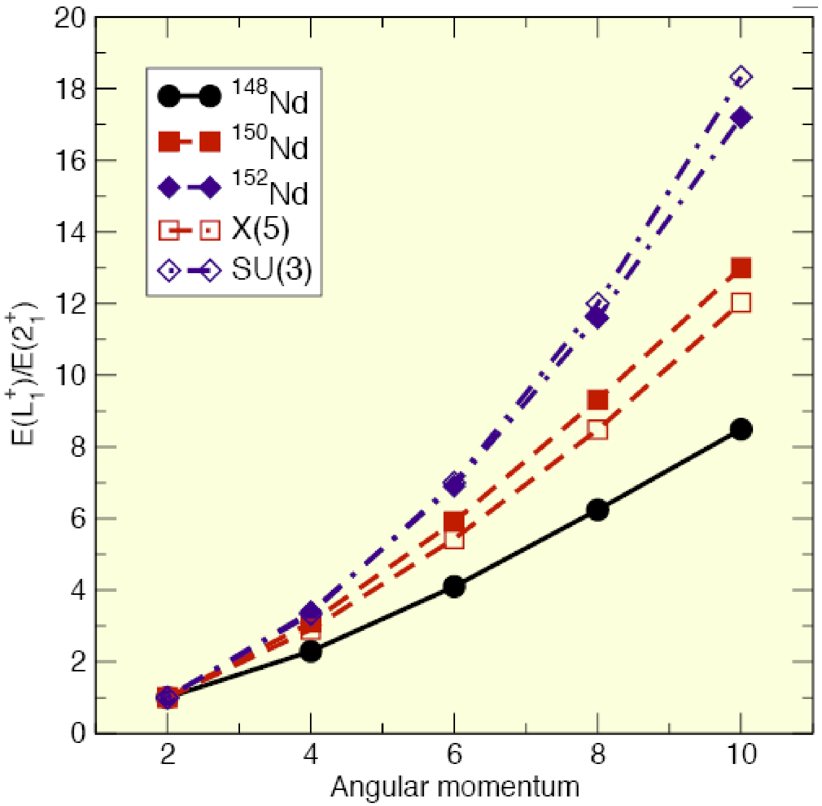
B(E2; L → L-2) values and excitation energies for the yrast states: **^{148}Nd**, **^{150}Nd**, and **^{152}Nd**, calculated with the GCM and compared with those predicted by the **X(5)**, **SU(3)**





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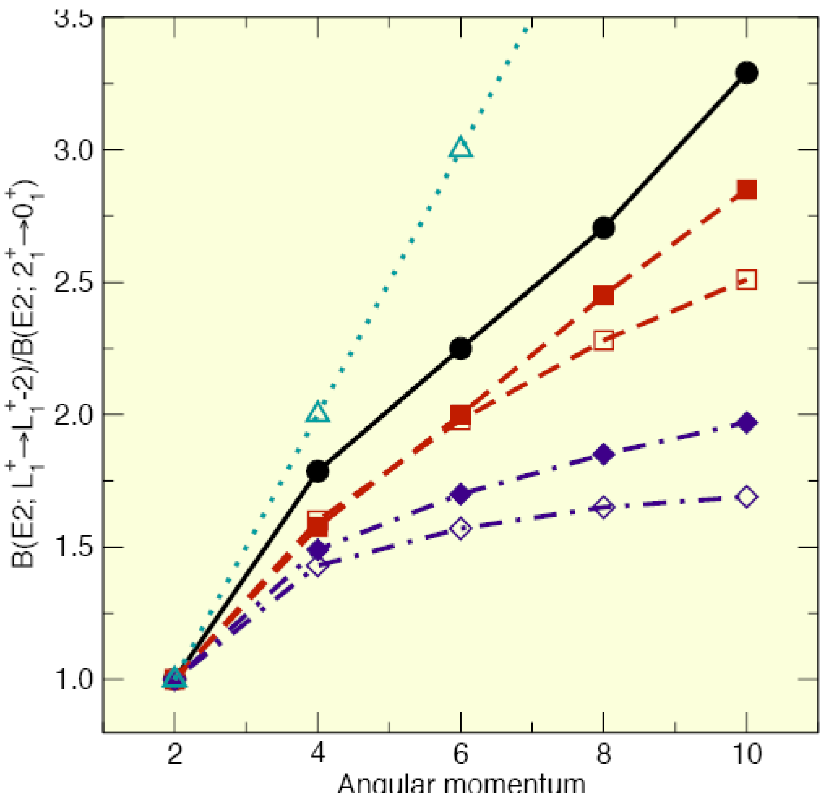
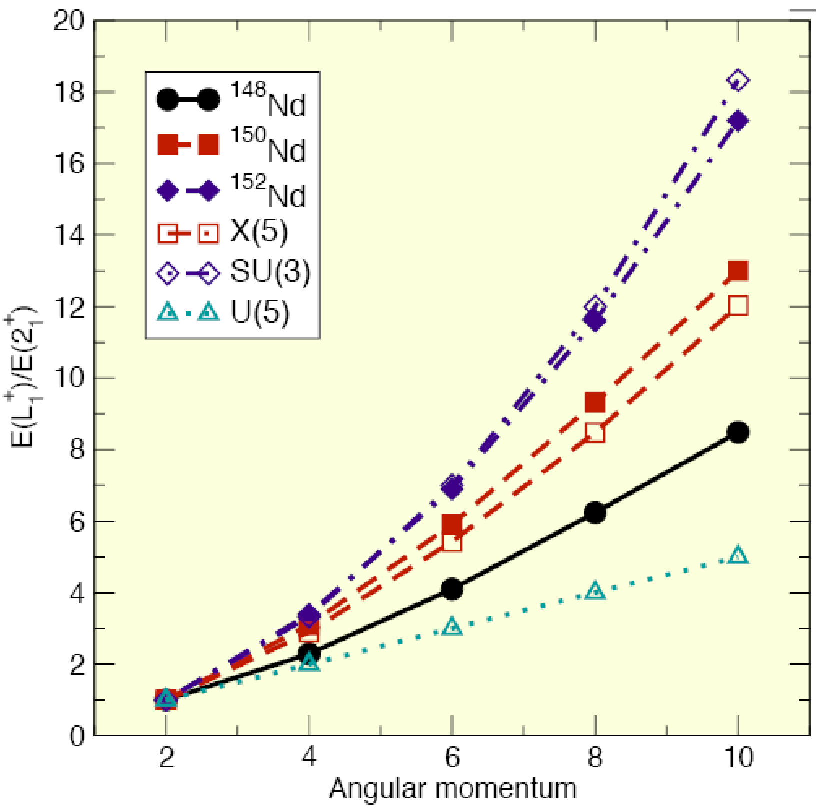
B(E2; L → L-2) values and excitation energies for the yrast states: **^{148}Nd**, **^{150}Nd**, and **^{152}Nd**, calculated with the GCM and compared with those predicted by the **X(5)**, **SU(3)** and **U(5)** symmetries.





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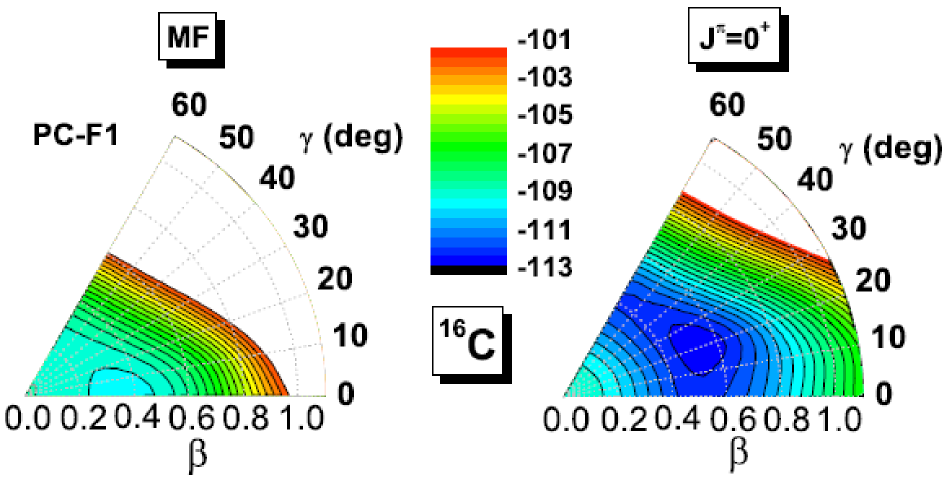
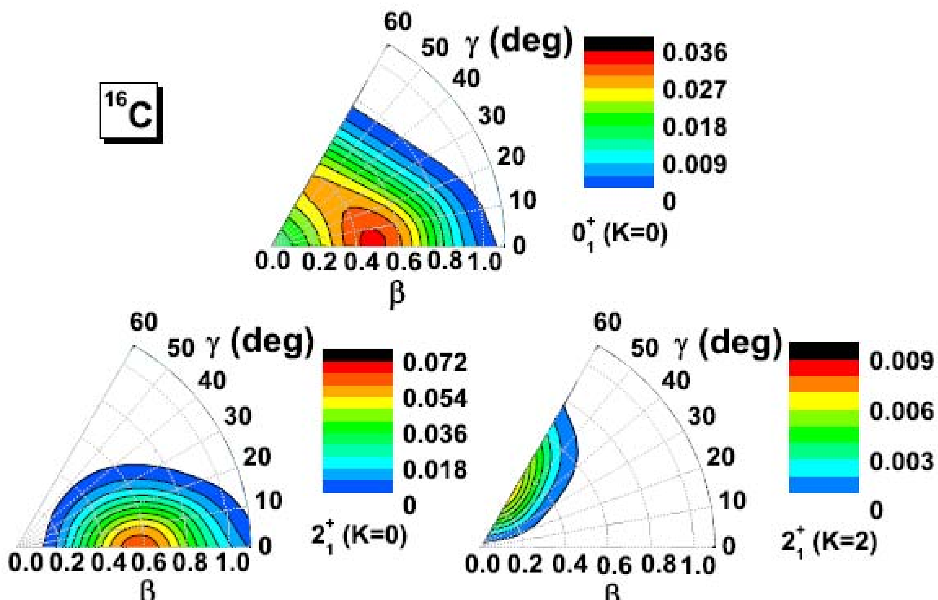
potential energy suface:

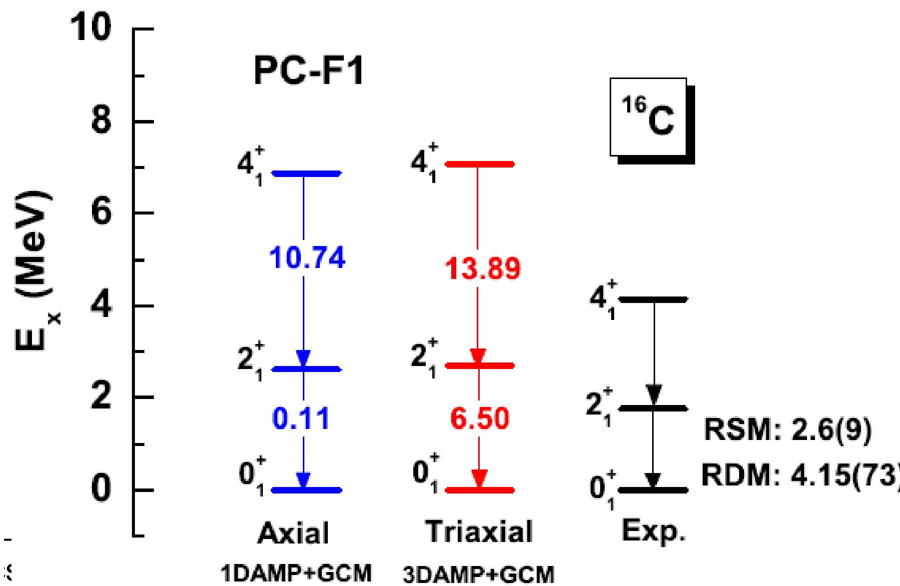


First relativictic full 3D GCM calculations

Yao et al, PRC 81, 044311 (2010)

collective wave functions:





triaxial GCM in q=(β,γ) is approximated by the diagonalization of a 5-dimensional Bohr Hamiltonian:

Bohr Hamiltonian: $H = -\frac{\partial}{dq}\frac{1}{2B(q)}\frac{\partial}{dq} + V(q) + V_{corr}(q)$

the potential and the inertia functions are calculated microscopically from rel. density functional

Theory:	Banerjee and Brink (1973)	(from GCM)
	Giraud and Grammaticos (1975)	(from GCM)
	Baranger and Veneroni (1978)	(from ATDHF)
Skyrme:	J. Libert, M. Girod, and J.-P. Delaroche (1999)	
RMF:	L. Prochniak and P. R. (2004)	
	Niksic, Li, et al (2009)	
Gogny	DelaRoche et al (2010)	

Inertia parameters:

$$\mathcal{M}^{-1} = \begin{pmatrix} A & -B \\ -B^* & A^* \end{pmatrix} = \mathcal{M}_0^{-1} + \mathcal{V}$$

$$\mathrm{B}_{\mu\mu'}(\mathbf{q}) = \frac{1}{\hbar^2} \begin{pmatrix} P^* & -P \end{pmatrix}_{\mu} \mathcal{M} \begin{pmatrix} P \\ -P^* \end{pmatrix}_{\mu'}$$

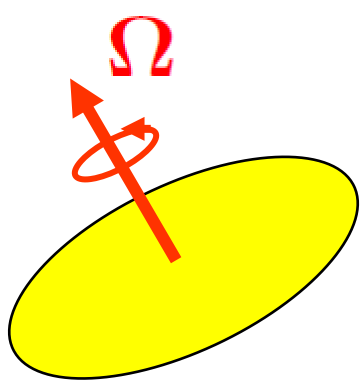
$$\left(\mathcal{M}_0^{-1}\right)_{php'h'} = (\epsilon_p - \epsilon_h)\delta_{pp'}\delta_{hh'}$$

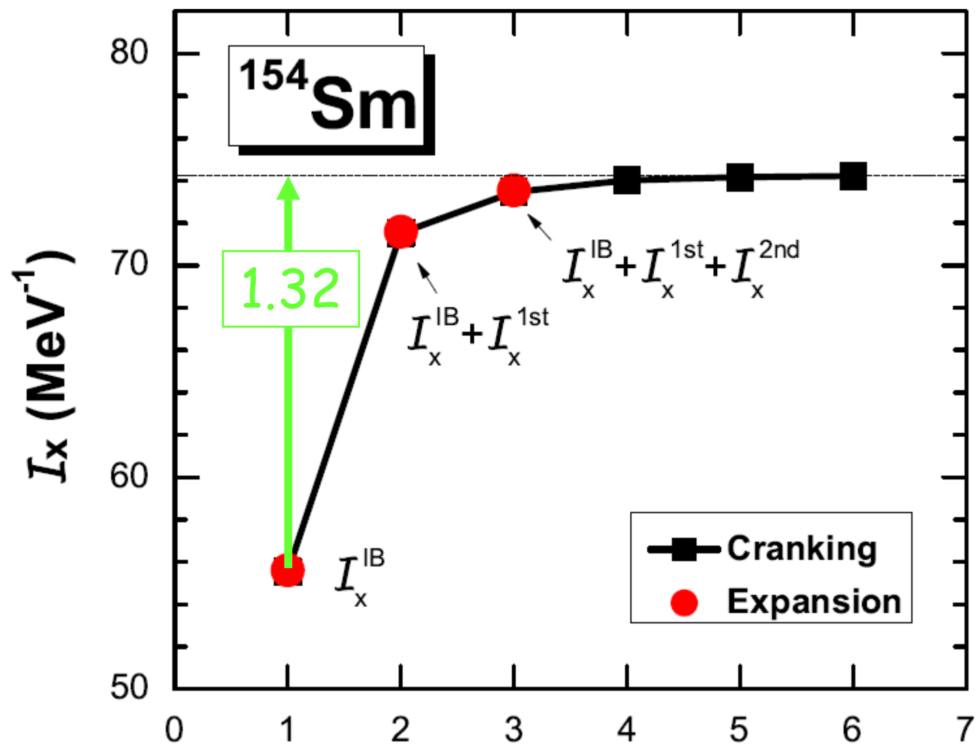
$$\mathcal{M} = \mathcal{M}_0 \left[\mathbb{1} + \mathcal{V}\mathcal{M}_0\right]^{-1}$$

Thouless-Valatin mass

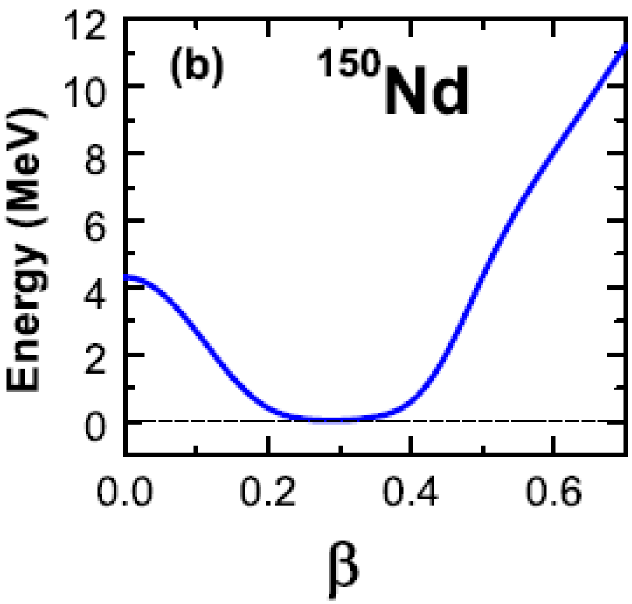
$$\mathcal{M} = \mathcal{M}_0 - \mathcal{M}_0\mathcal{V}\mathcal{M}_0 + \mathcal{M}_0\mathcal{V}\mathcal{M}_0\mathcal{V}\mathcal{M}_0 + \cdots .$$

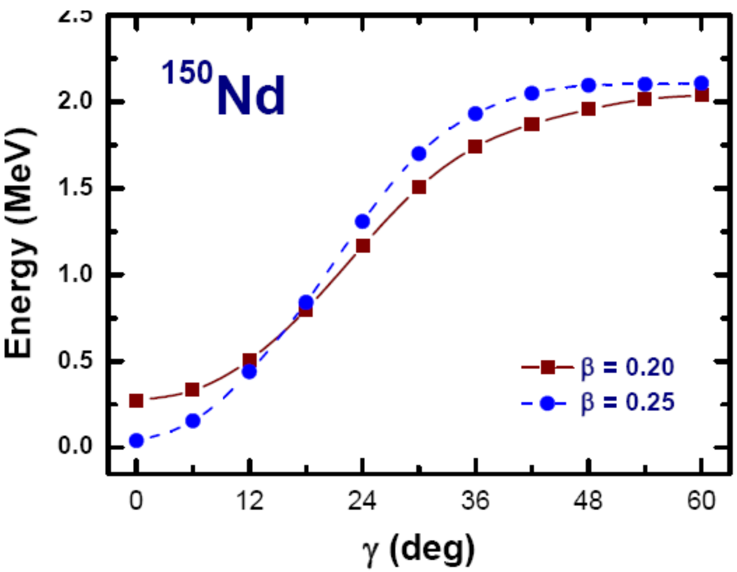
An example:
Rotational inertia
here we can use the self-consistent cranking model

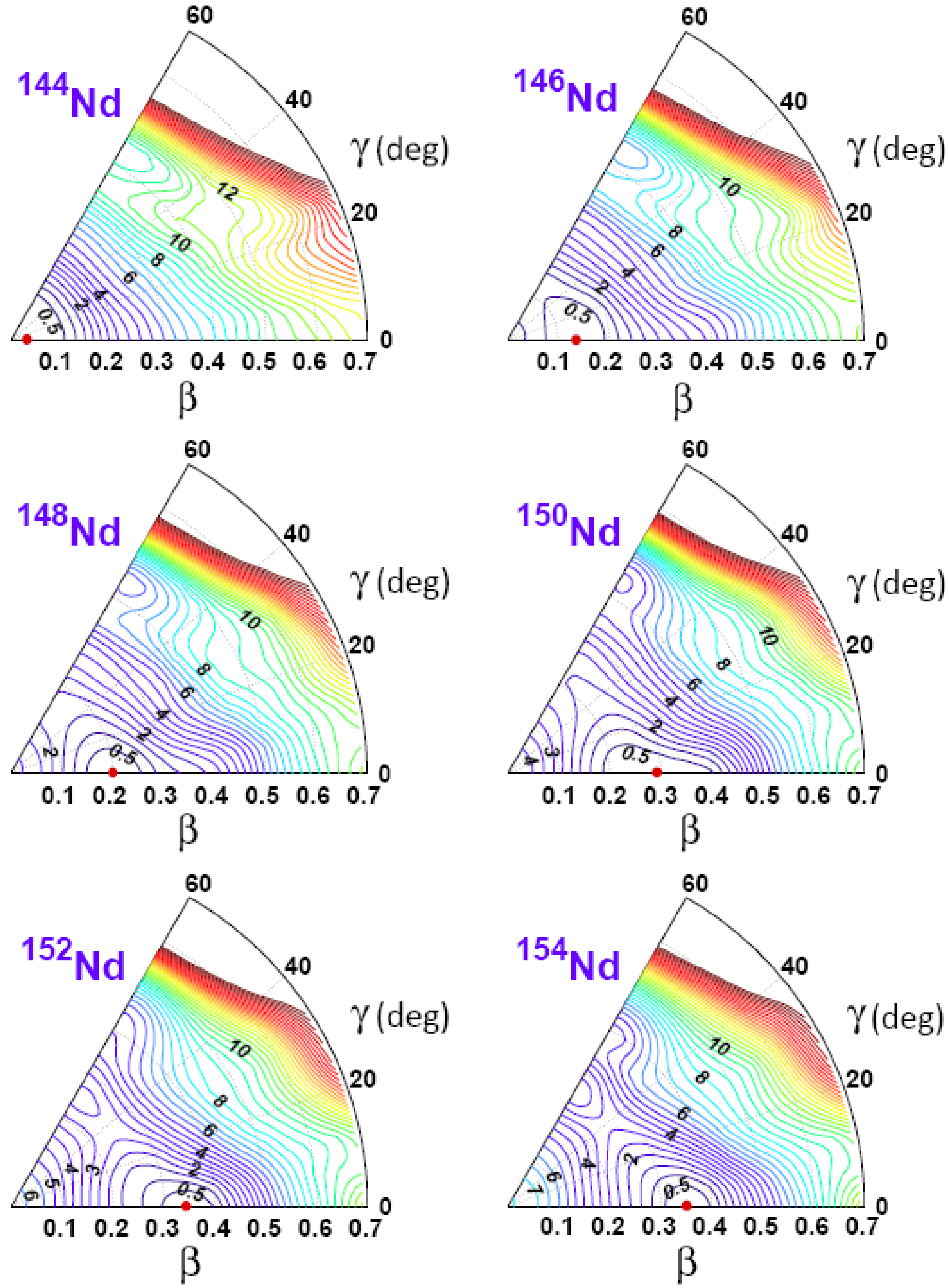




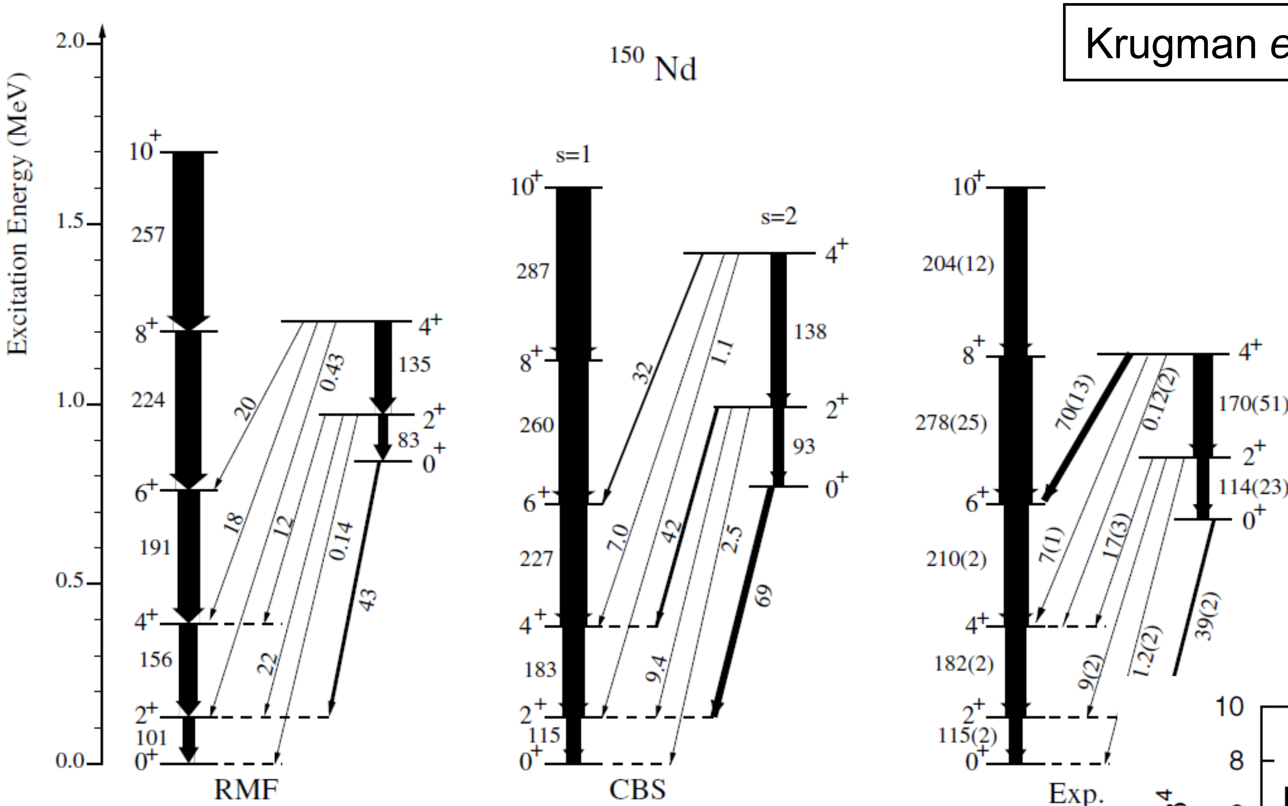
Potential energy surfaces:



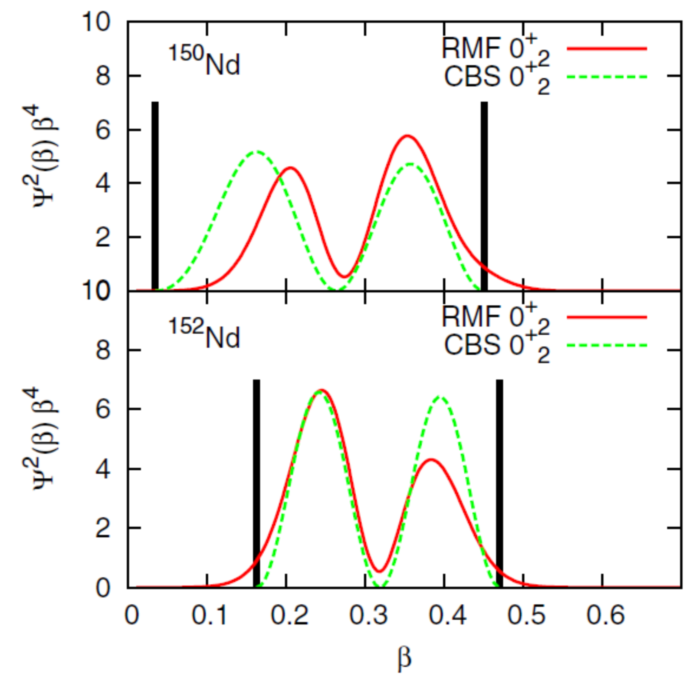




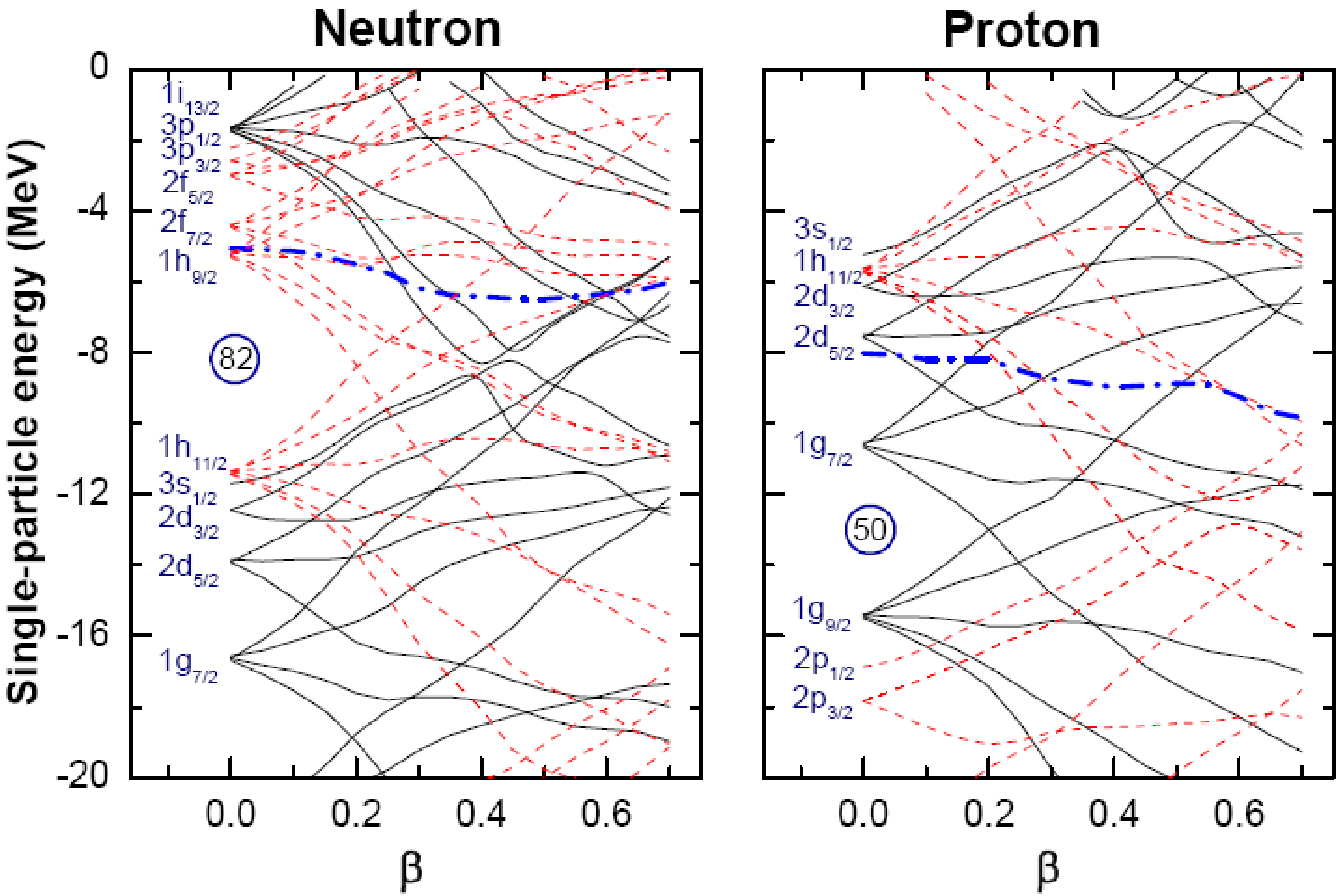
Krugman *et al* JPG 38 (2011)



Comparison: β-soft rotor (CBS)



neutron and proton levels for ^{150}Nd



Questions:

- How much are the discontinuities **smoothed out** in finite systems ?
- How well can the phase transition be associated with a certain value of the control parameter that takes **only integer values** ?
- Which experimental data show discontinuities in the phase transition?

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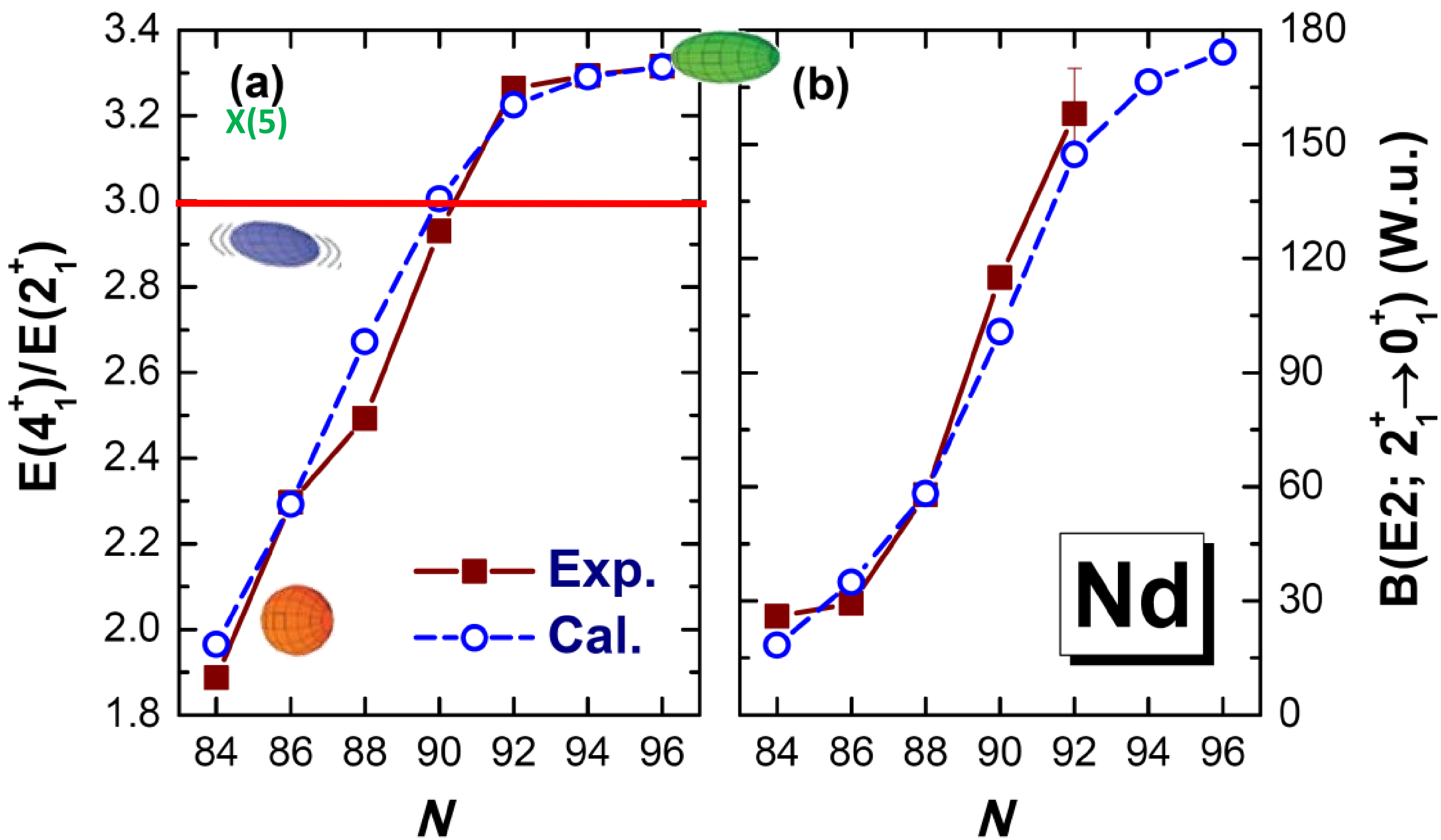
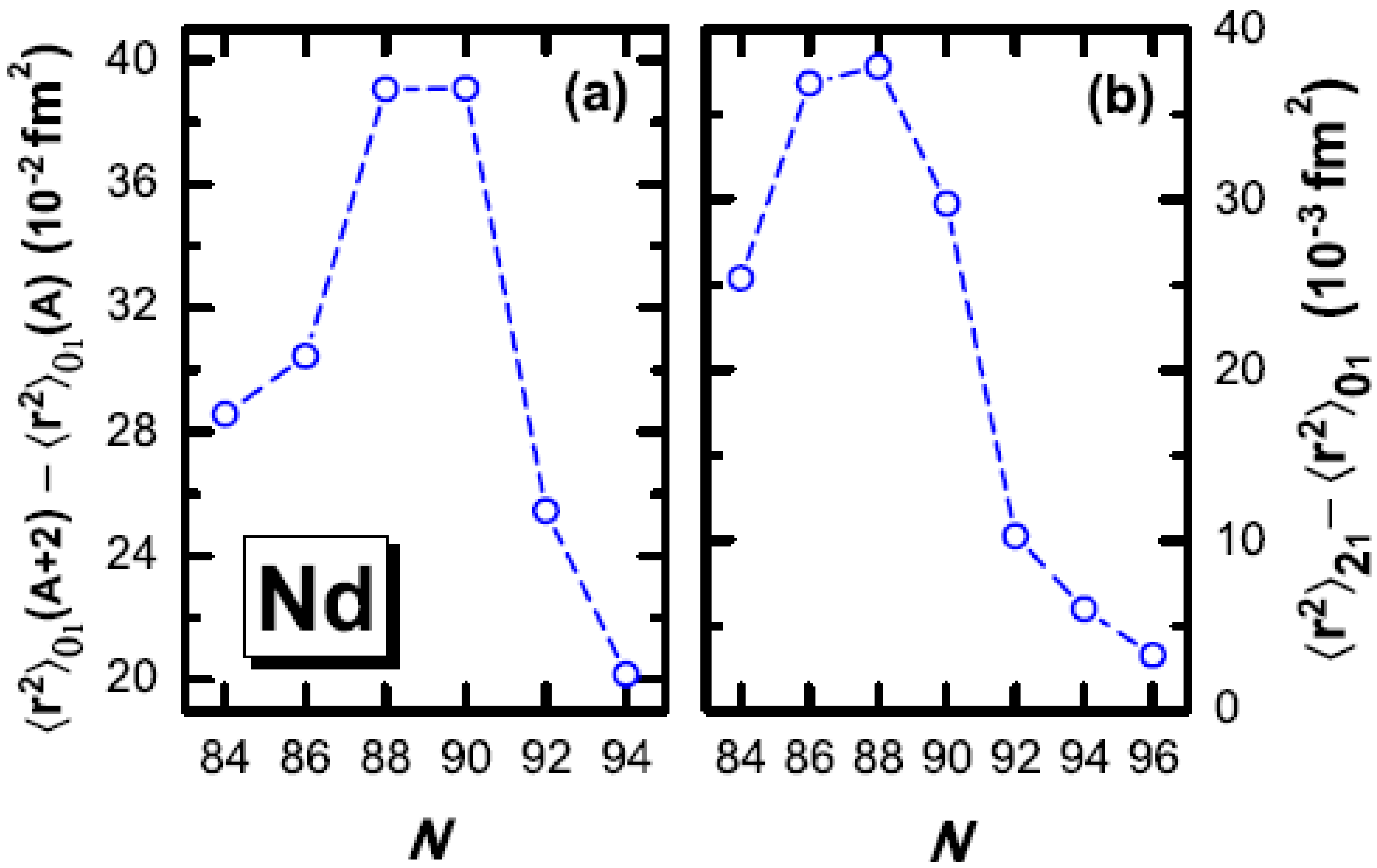
Sharp increase of $R_{42}=E(4_1)/E(2_1)$ and $B(E2;2_1\text{-}0_1)$:



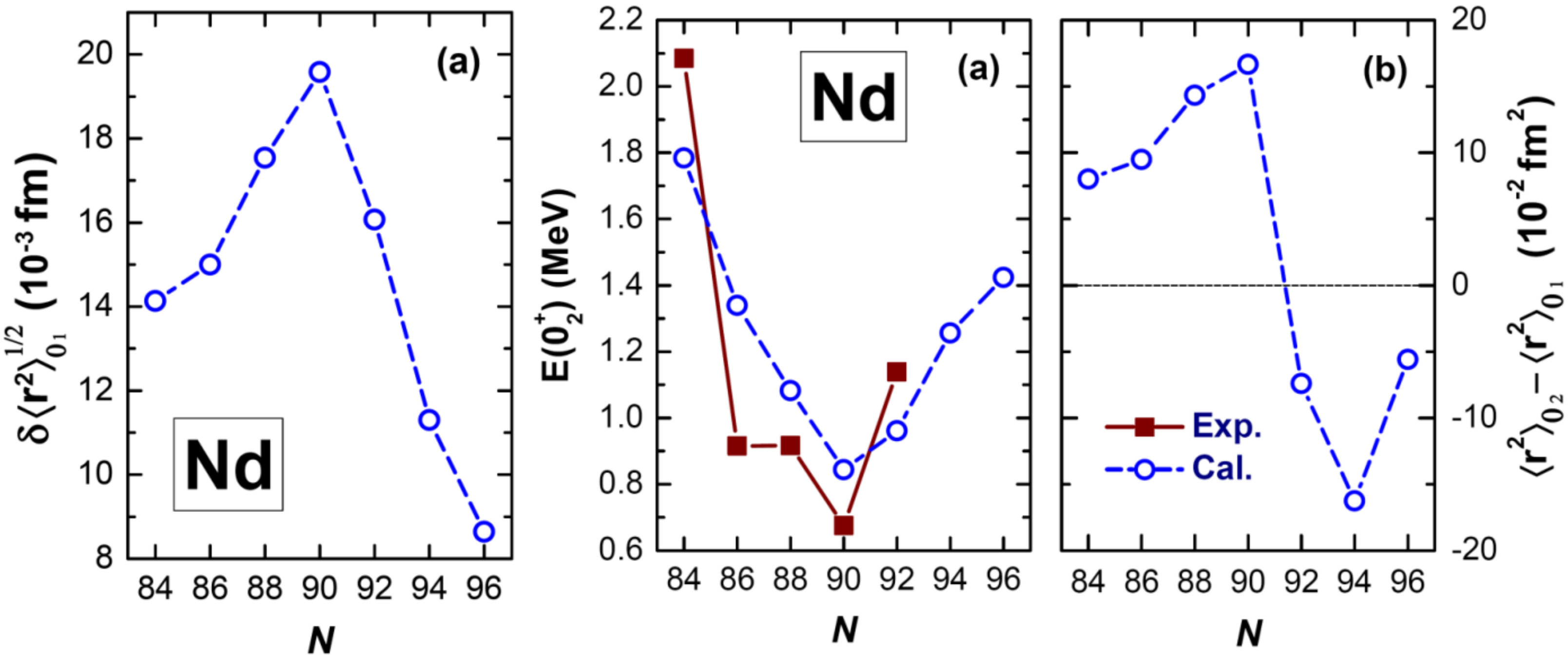
Li, Niksic *et al* PRC 79 (2009)

Isomeric shifts in the charge radii:



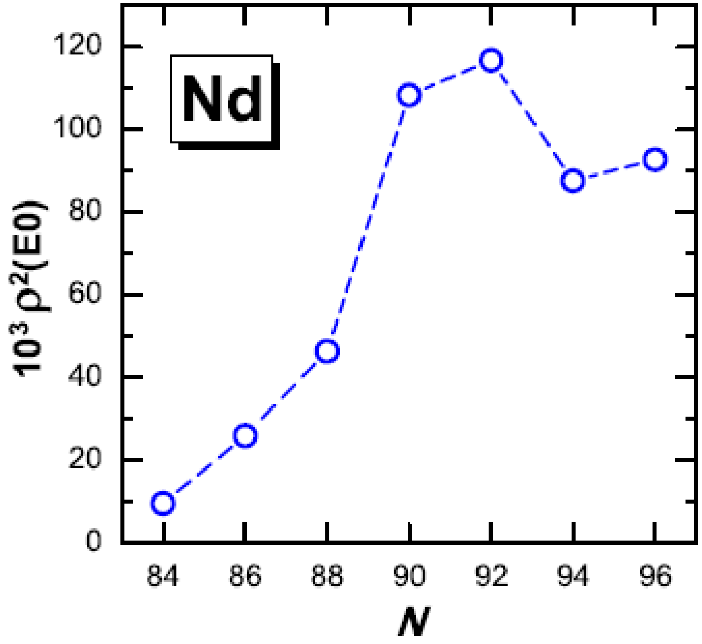
Li, Niksic *et al* PRC 79 (2009)

Properties of 0^+ excitations



Li, Niksic *et al* PRC 79 (2009)

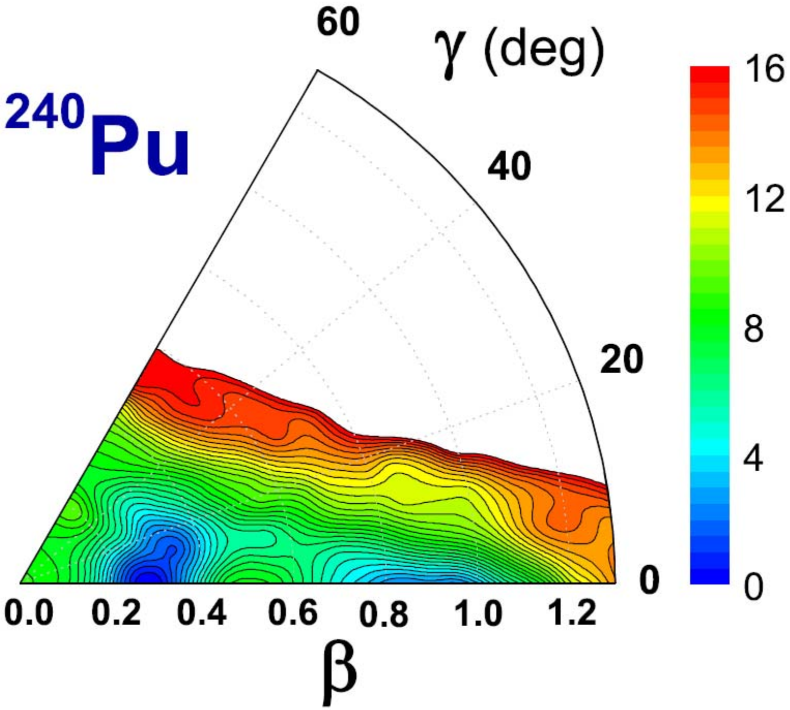
Monopol transition strength $\rho(E0; 0_2 - 0_1)$



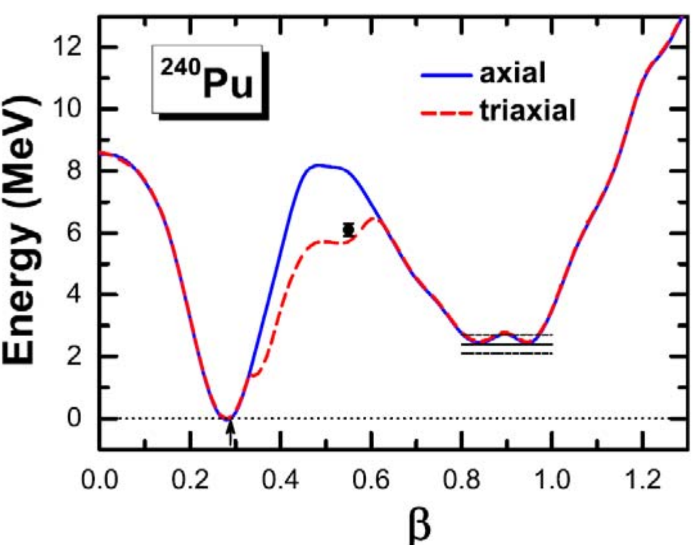
Li, Niksic *et al* PRC 79 (2009)

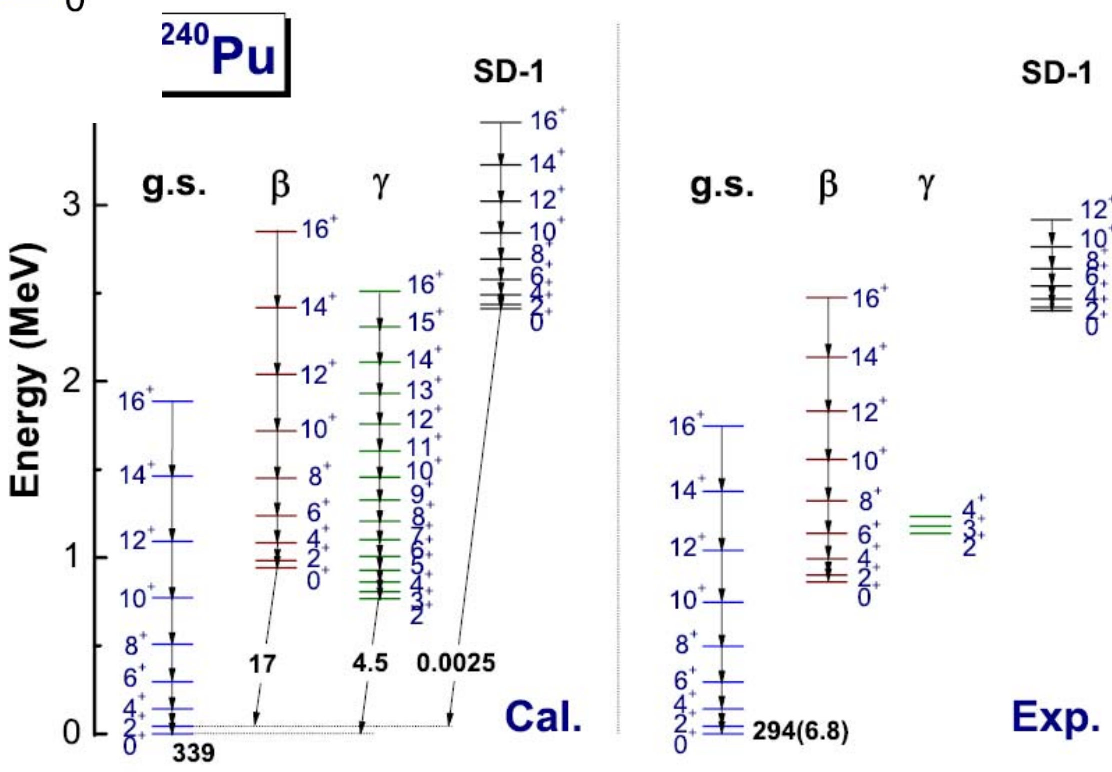
Fission barrier and super-deformed bands in ^{240}Pu

Niksic *et al* PRC 79 (2009)



DD-PC1





Conclusions:

GCM calculations for spectra in transitional nuclei

- J+N projection is important,
- triaxial calculations so only for very light nuclei possible
- microscopic theory of quantum phase transitions

Derivation of a collective Hamiltonian

- allows triaxial calculations
- nuclear spectroscopy based on density functionals
- open question of inertia parameters

The microscopic framework based on universal density functionals provides a consistent and (nearly) parameter free description of quantum phase transitions

The finiteness of the nuclear system does **not seem to smooth** out the discontinuities of these phase transitions

Collaborators:

T. Niksic (Zagreb)
D. Vretenar (Zagreb)

G. A. Lalazissis (Thessaloniki)

L. Prochniak (Lublin)

Z.P. Li (Beijing)
J.M. Yao (Chonqing)
J. Meng (Beijing)

Thank you

and

Happy Birthday to you, Franco