Role of Multiphonon Configurations on Nuclear Spectra and Giant Resonances

.

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Oslo09

- A QPM study of low-lying spectra in heavy nuclei

  in collaboration with

  Ch. Stoyanov (Sofia) (spherical nuclei)

  A.V. Sushkov (Dubna) (deformed nuclei)

- A new multiphonon approach and its implementation on ^{16}O

  Collaborators:

  F. Andreozzi, A. Porrino (Napoli)

  F.Knapp, J. Kvasil (Prague)

Multiphonon excitations: Exp. evidence

* High-energy

(N. Frascaria, NP A482, 245c(1988);
T. Auman, P.F. Bortignon, H. Hemling, Ann. Rev. Nucl. Part. Sc. 48, 351 (1998))

Double

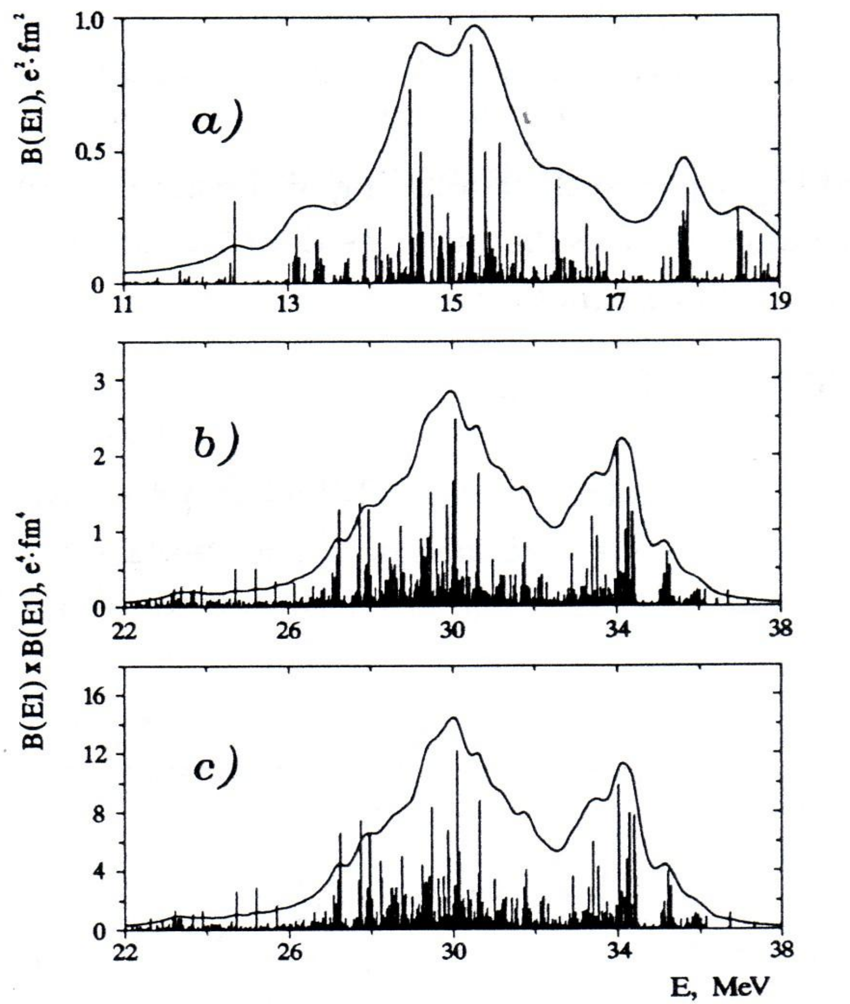
$$D \times D|0>$$

and

triple

$$D \times D \times D|0>$$

dipole giant resonances



Multiphonon excitations: Exp. evidence

** Low-energy

M. Kneissl. H.H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. 37, 439 (1996); M. Kneissl. N. Pietralla, and A. Zilges, J.Phys. G, 32, R217 (2006) :

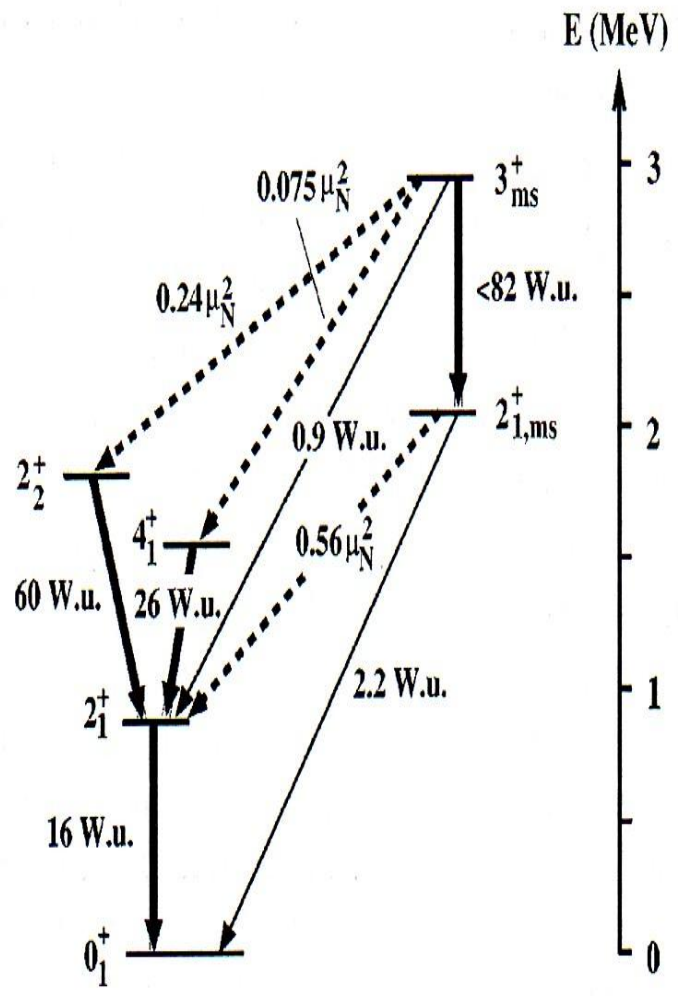
- Two- and three-phonon multiplets

$Q_2 \times Q_3|0\rangle$, $Q_2 \times Q_2 \times Q_3|0\rangle$

- In particular:

  Proton-neutron (F-spin) mixed-symmetry states

  (N. Pietralla et al. PRL 83, 1303 (1999))



π-ν Symmetric and MS states

Symmetric

$|n, \nu\rangle_s = Q_S^n\ |0\rangle = (Q_p + Q_n)^n\ |0\rangle$

MS

$|n, \nu\rangle_{MS} = (Q_p - Q_n)\ (Q_p + Q_n)^{(n-1)}\ |0\rangle$

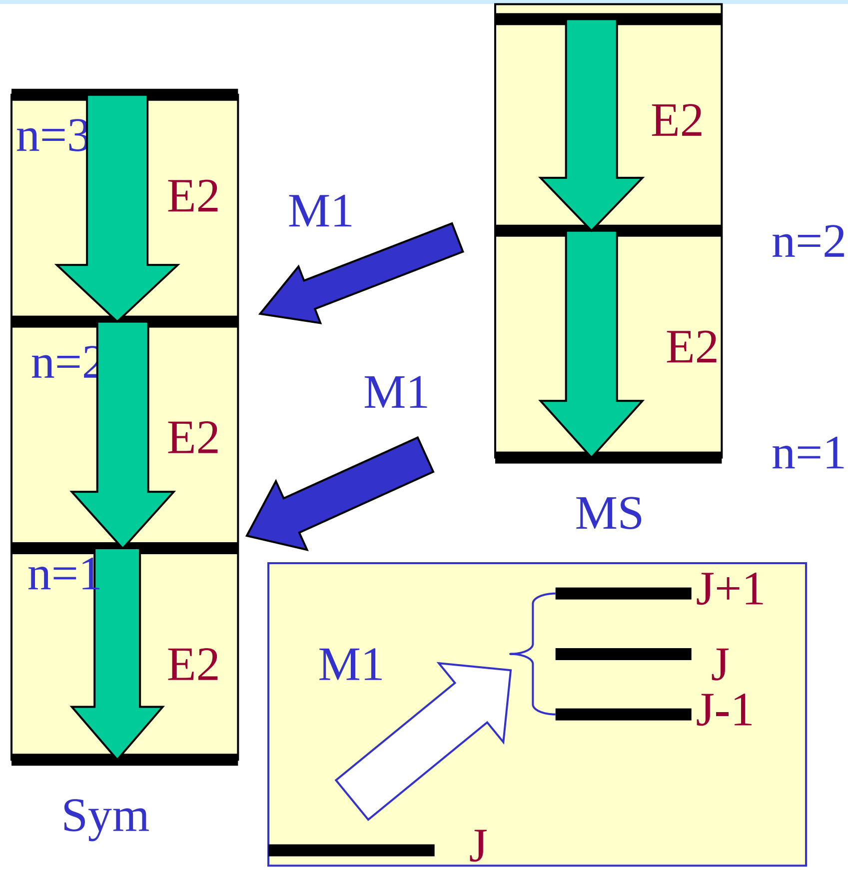
Signature: Transitions

$\mathcal{M}(E2) \propto Q_S \quad n \rightarrow n-1 \quad (\Delta n=1)$

symmetry preserving (ΔF=0)

$\mathcal{M}(M1) \propto J_n - J_p \quad n \rightarrow n \quad (\Delta n=0)$

symmetry changing (ΔF=1)



Scissors multiplet

$S\ |\ n,J\rangle = (J_p - J_n)\ |nJ\rangle$

$= \Sigma_{J'}\ |n\ J'\rangle \langle nJ'|\ S|nj\rangle$

$B_{sc}(M1) = \Sigma_{J'}\ |\langle nJ|\mathcal{M}(M1)|nJ\rangle|^2$

$\sim 1.5 - 2\ \mu_N^2$

A QPM analysis (N.L. and Ch. Stoyanov PRC (00) …(08)

A brief outline of QPM (Soloviev, Theory of Atomic Nuclei: Quasiparticles and Phonons, Bristol, (1992))

$$H = H_{sp} + V_{pair} + V_{pp} + V_{ff}$$

$$H[(a^\dagger a), (a^\dagger a^\dagger), (aa)] \Rightarrow H[(\alpha^\dagger \alpha), (\alpha^\dagger \alpha^\dagger), (\alpha \alpha)]$$

(ph) (qp)

RPA phonons

$$\left\{ \begin{matrix} \alpha^\dagger \alpha^\dagger \\ \alpha\, \alpha \end{matrix} \right\} \Longrightarrow \left\{ \begin{matrix} O^\dagger_\lambda \\ O_\lambda \end{matrix} \right\}$$

$$O_\lambda^\dagger = \Sigma_{kl} \left[X_{kl}(\lambda)\, \alpha^\dagger_k\, \alpha^\dagger_l - Y_{kl}(\lambda)\, \alpha_k\, \alpha_l \right]$$

QPM (continue)

$$H = H_{sp} + V_{pair} + V_{pp} + V_{ff}$$

⇓

$$\mathbf{H_{QPM} = \Sigma_{n\lambda}\, \omega_n(\lambda)\, Q^{\dagger}_{\lambda}\, Q_{\lambda} + H_{vq}}$$

⇓

$$\Psi_\nu = \Sigma_n c_n\, Q^{\dagger}_{\nu}(n)\, |0> + \Sigma_{ij} C_{ij}\, Q^{\dagger}(i)\, Q^{\dagger}(j)\, |0>$$
$$+ \Sigma_{ijk} C_{ijk}\, Q^{\dagger}(i)\, Q^{\dagger}(j)\, Q^{\dagger}(k)|0>$$

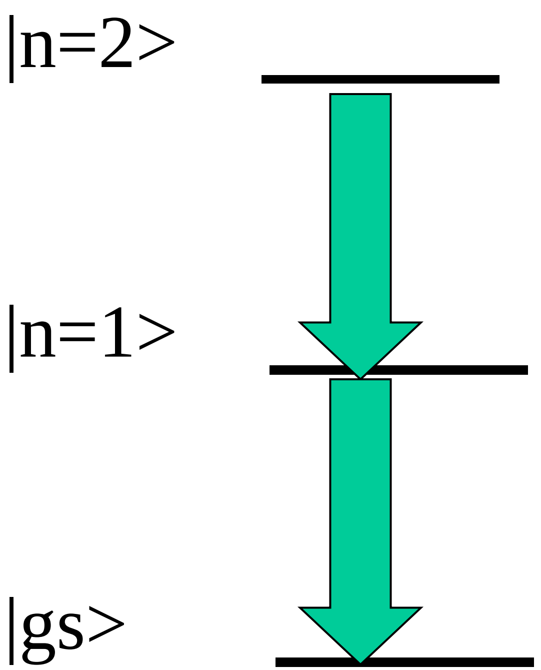
QPM systematics of low-lying spectra in nuclei in the proximity of N=50

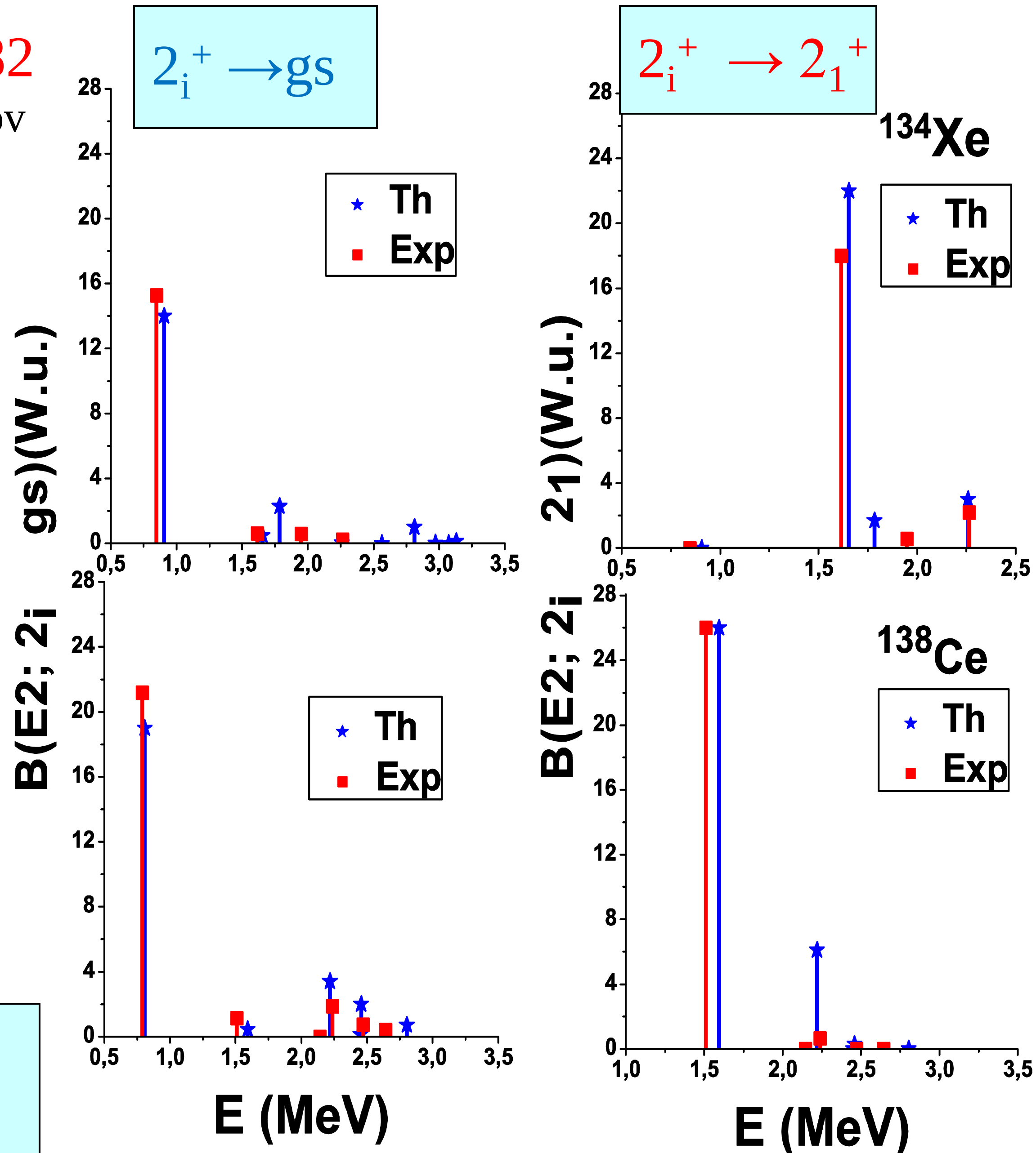
N.L. and Ch. Stoyanov, PRC (00)…..(06)

QPM spectra and transitions strengths are consistent with Experiments and IBM

MS in nuclei near N=82

N.L., Ch. Stoyanov, D.Tarpanov
PRC 77 (08)





E2 Transitions

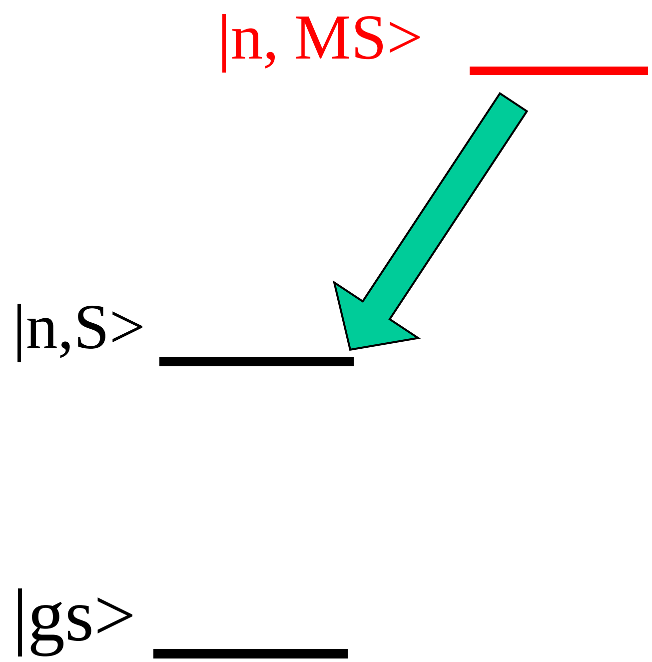
($\Delta F=0$, $\Delta n=1$)

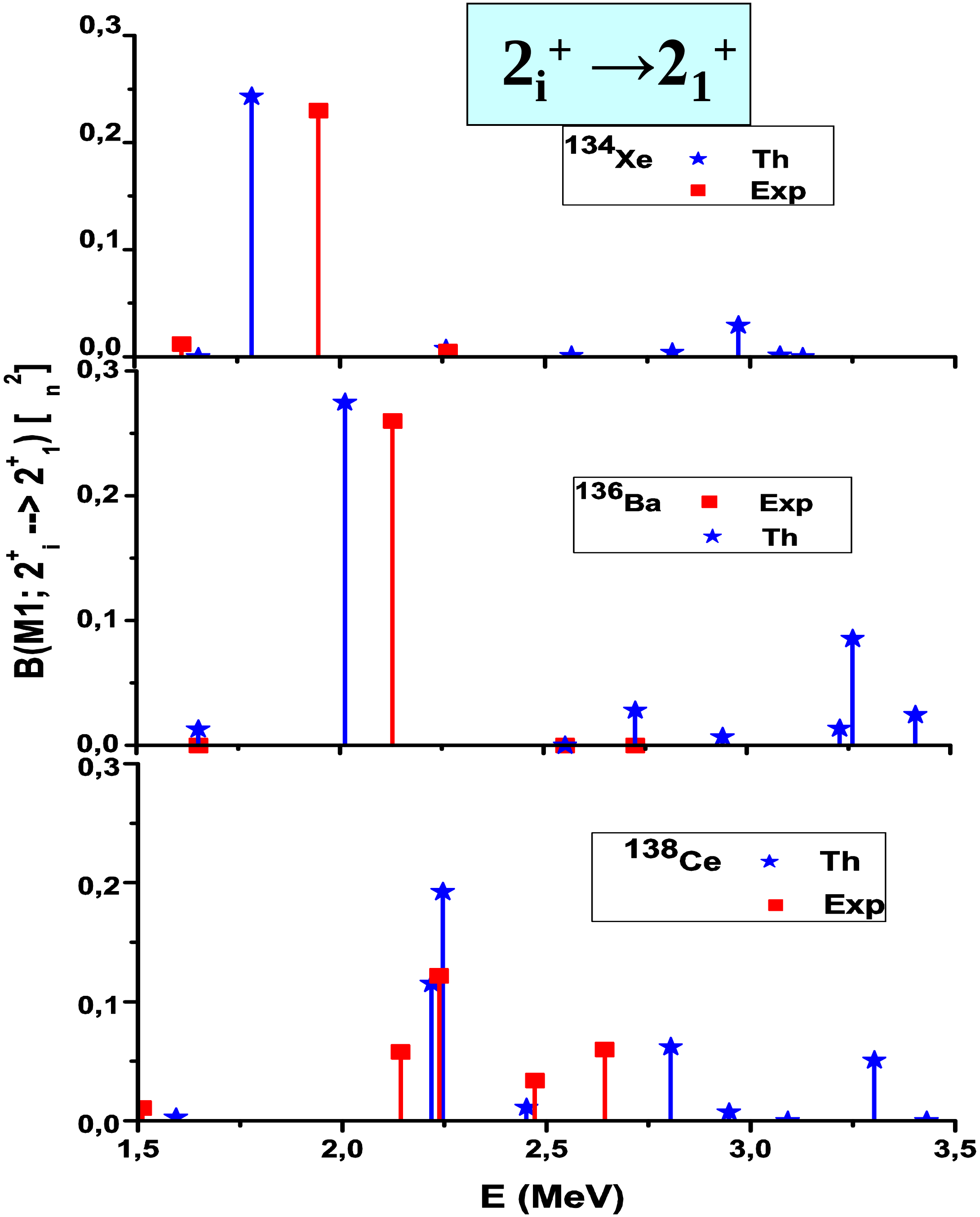
N=80

M1 Transitions

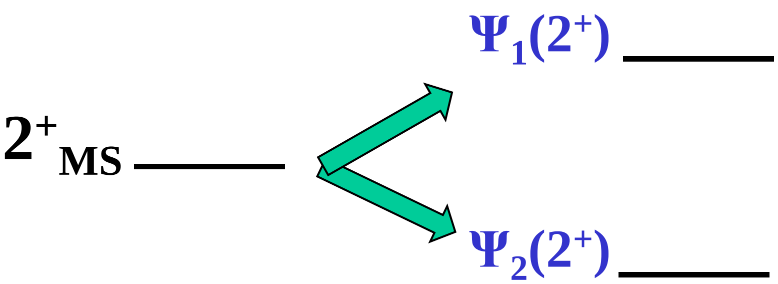
(Δn=0, ΔF= 1)

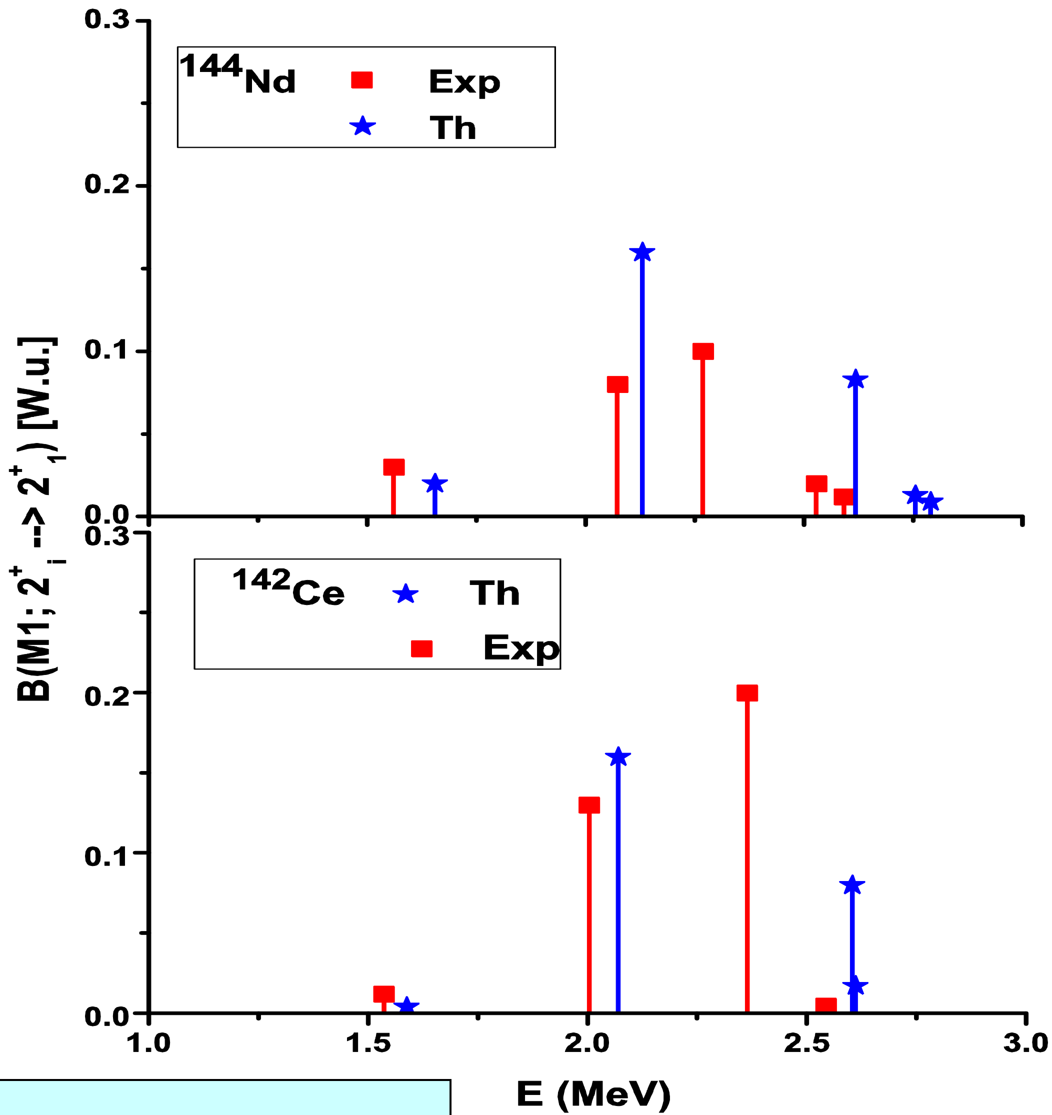
QPM versus EXP





Splitting of B(M1) in N=84 isotones





Why the splitting?
Phonon coupling
induced by the neutron shell structure in N=84 nuclei

$$\Psi_1(2^+) = c_1 | n=1, 2^+ >_{MS} + c_2 |n=2> + c_3 |n=3>$$

$$\Psi_2(2^+) = b_1 | n=1, 2^+ >_{MS} + b_2 |n=2> + b_3 |n=3>$$

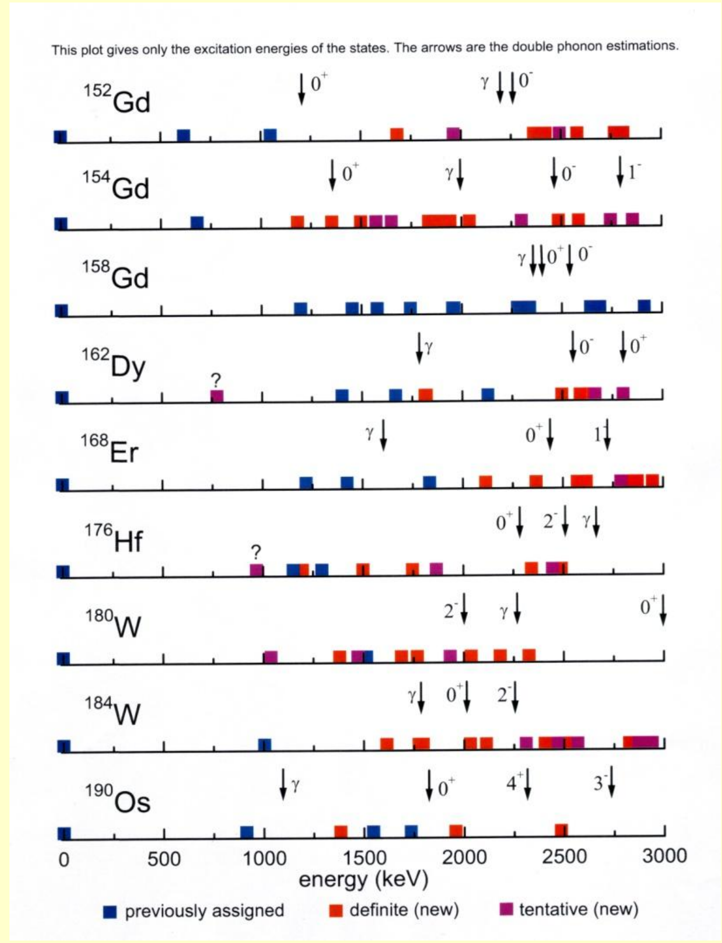
Deformed Nuclei: From one to many 0^+

The issue:
Large abundance of 0+ levels populated in (p,t) experiments on

^{158}Gd n=13 0+ (E< 3.2 MeV)
(Lesher *et al*. PRC 66, 051305(R) (2002))

^{228}Th, ^{230}Th and ^{232}U
n~10 (E< 3.0 MeV)
(Wirth et al. PRC 69, 044310 (2004))

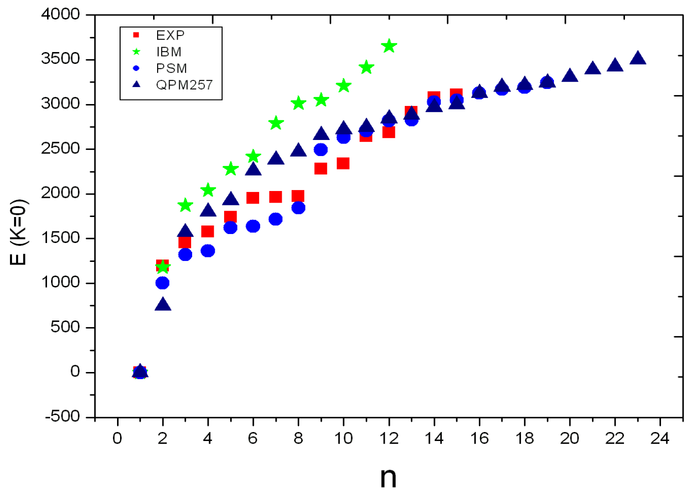
^{168}Er n~ 25 !! (E < 4 MeV)
D. Bucurescu et al., PRC 73, 064309 (2006)

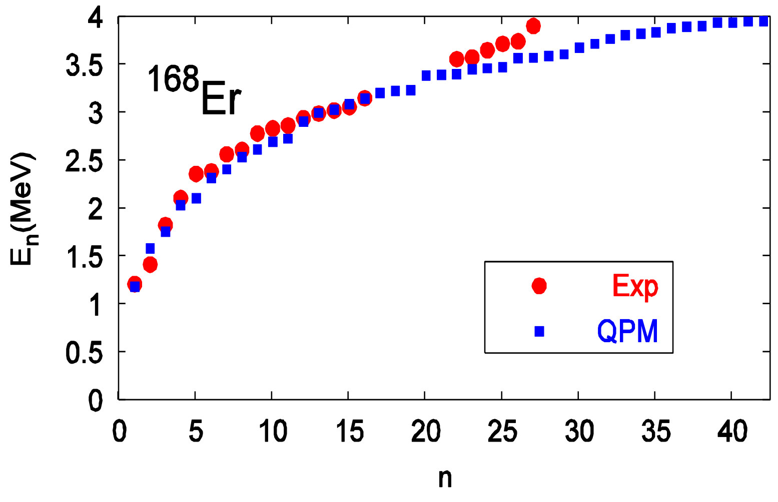


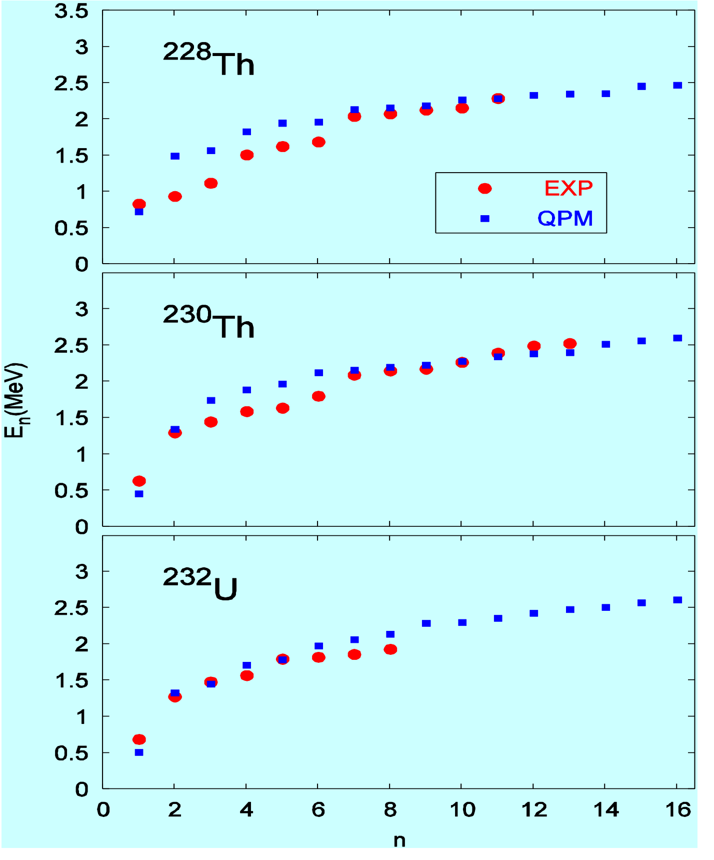
Systematic
D. A. Meyer et al., PRC 74, 044309 (2006) and references therein

QPM accounts for all 0^+ levels and even more!!

N.L. A.V. Sushkov, N. Yu. Shirikova PRC 70 (04); PRC 72 (05)







Can QPM give
some insight
on the nature of these 0^+ ?

Quadrupole collective (β-band)?

$|K^{\pi}=0^{+}\rangle \sim Q_0|0\rangle$?

$B(E2,\ 0^{+}\rightarrow 2_g^{+}) \ll B_{vib}(E2) \sim \langle 0|Q_0^{2}|0\rangle \sim 33$ w.u.

(P. E. Garrett J. P. G 27 (2001) R1)

$B(E0) \ll B_{vib}(E0) \sim \langle 0|(r^2)^2|0\rangle/\langle 0|r^2|0\rangle^2 \sim 85 \div 230\ (10\text{-}3)$

J. L. Wood et al. Nucl. Phys. A651 (1999) 323

$|K^{\pi}=0^{+}\rangle \sim Q_0|0\rangle$? **No !!**

But we need more exp. information

Pairing vibration?

$<0 | P_0^2 \; |0> \sim |<n=1K=0| P_0|0>|^2 = \Gamma_1^2 (p,t)$

$P_0 = \Sigma_q \; a_q a_{-q}$

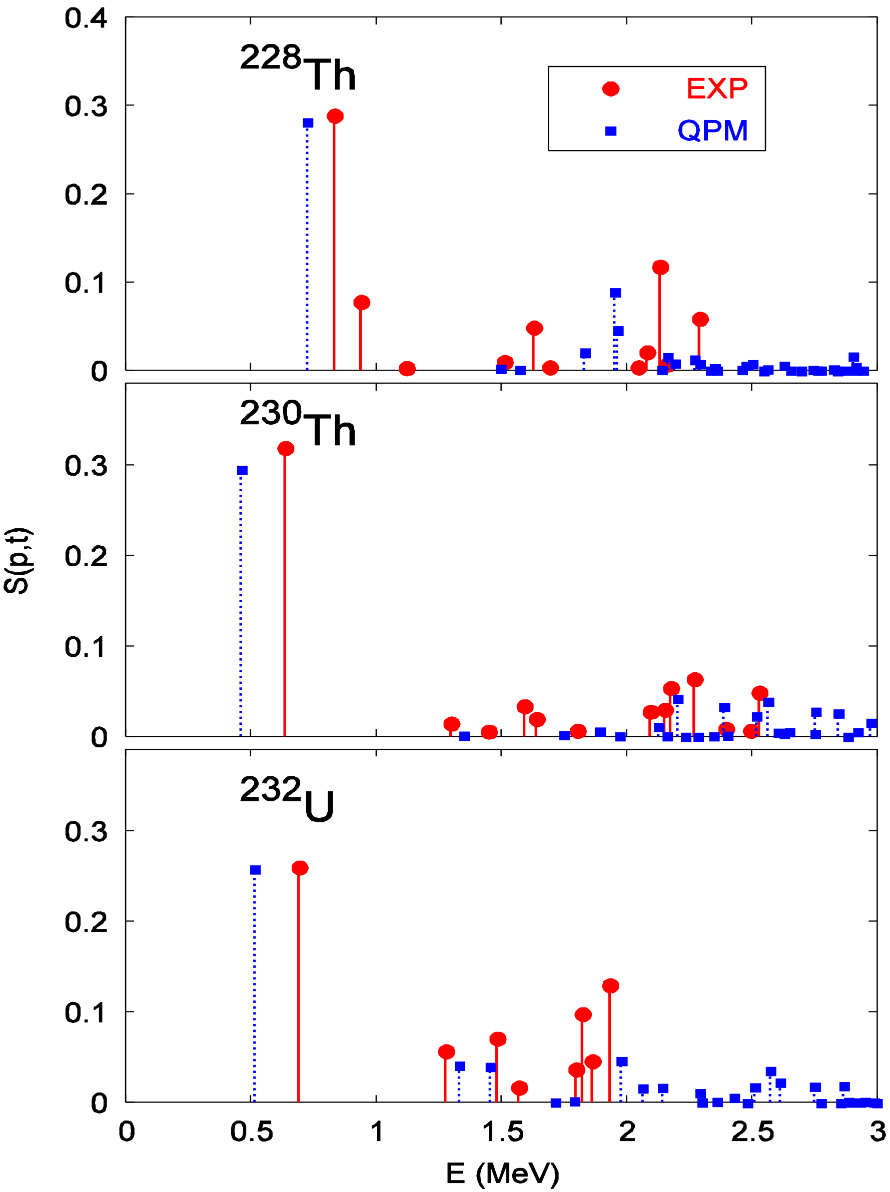
Normalized (p,t) spectroscopic factors

$S_n(p,t) = [\Gamma_n (p,t) / \Gamma_0 (p,t)]^2$

$\Gamma_0^2 (p,t) = <0|P_0|0>^2$

$\Gamma_n^2 (p,t) = <n|P_0|0>^2$

S(p,t) and pairing collectivity



RPA w.f.

$$|\,0^{+}\rangle_{RPA} \sim 0.46\,[(521\uparrow)(521\uparrow)] + 0.44\,[(505\uparrow)(505\uparrow)] + 0.39\,[(523\downarrow)(523\downarrow)] + 0.37\,[(411\uparrow)(411\uparrow)] + ..$$

Pairing acts **coherently** only in the **lowest RPA 0+** !!!

Fragmentation due to

i) s.p. decay (Landau damping)

ii) phonon coupling (collisional damping)
(spoils partly pairing coherence, especially in ^{168}Er)

Nature of 0^+ states

multiphonon excitations ? NO (in general)

$|\,0^+ > \sim |(\lambda x \lambda)^0 >$

Elementary one-phonon excitations ? Yes

Collective β**-vibrations?** **No!**

$|K^\pi=0^+> \quad \sim \quad Q_0|0>$

Pairing vibrations? **Yes**

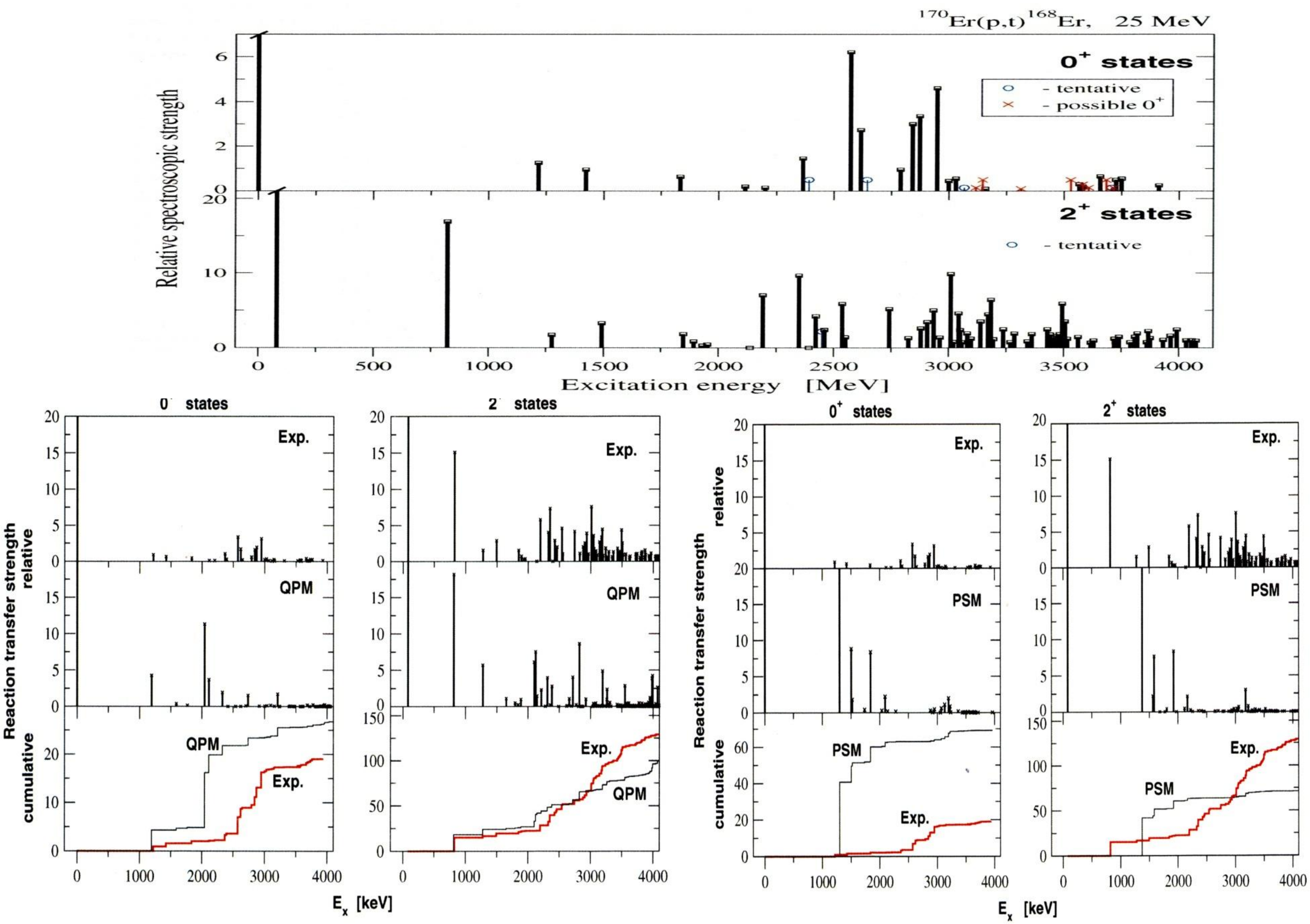
$|K^\pi=0^+> \; \sim \; P_0 \; |0> \; = G \, \Sigma \, a^\dagger_q \, a^\dagger_{-q} \, |0>$

More specifically

Damped Pairing vibrations

Due to phonon coupling

^{168}Er as a special case (Bucurescu et al., PRC 73, 064309 (2006))

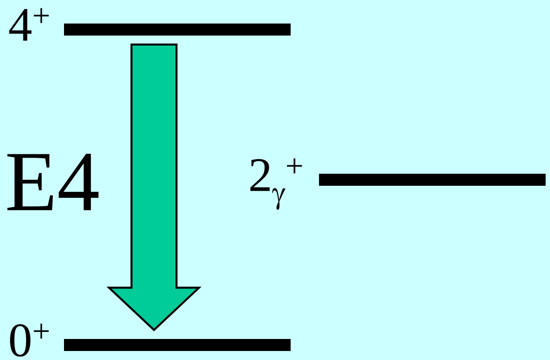


4^+ state in Os isotopes

N. Lo Iudice and A. V. Sushkov,   PRC 78, 054304 (2008).

Hexadecapole one-phonon?

$\Psi \sim |n=1,4+>$

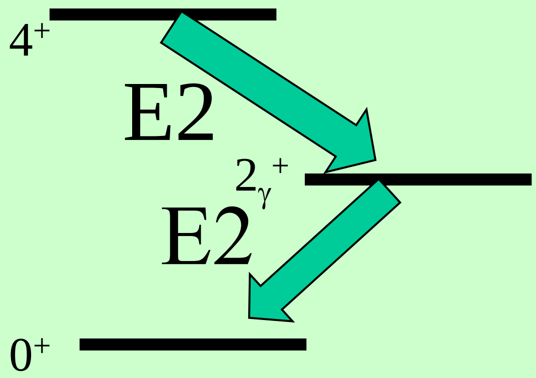


S(t,α)

Double-γ ?

$\Psi \sim \ |\gamma\gamma>$

$E_4 \sim 2\ \ E_\gamma$



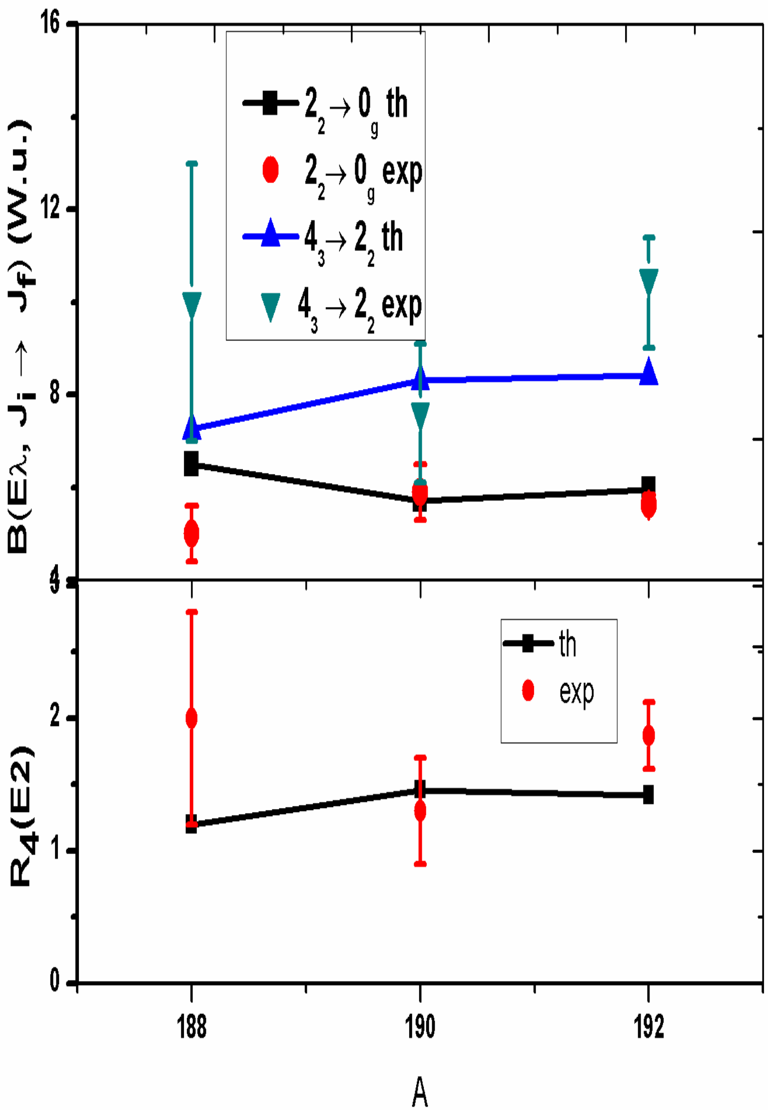
$R_4(E2) = B(E2,4^+ \rightarrow 2^+)/B(E2,2^+ \rightarrow 0^+)$

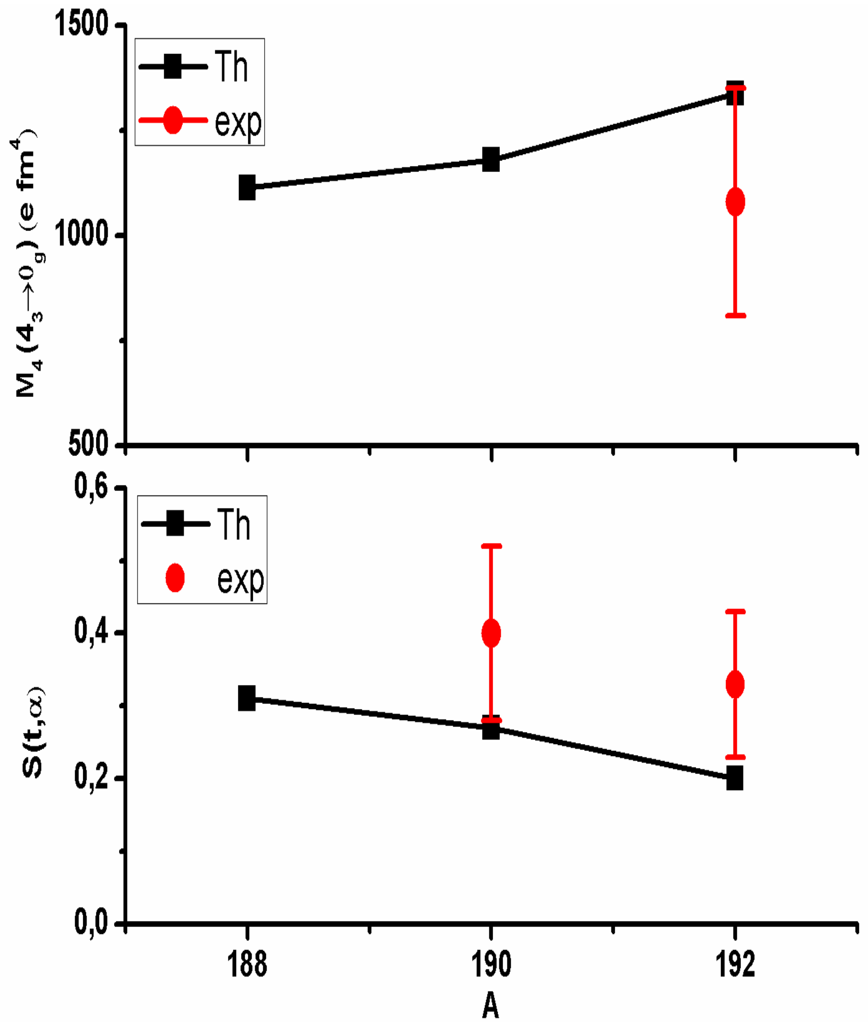
~ 2

QPM

$\Psi \sim 0.60\ |n=1,4+> \ + 0.35\ |\gamma\gamma>$

4^+: QPM versus EXP





A new multiphonon approach

Aim: Generate iteratively a multiphonon basis

$$|n;\beta\rangle = \Sigma_{\alpha\lambda} C^{(n)}_{\alpha\lambda} O^{\dagger}_{\lambda} |n-1;\alpha\rangle$$

n≡ number of TDA phonons

Adopt | n; β> to solve

$$H|\Psi_\nu\rangle = E_\nu |\Psi\nu\rangle \qquad \ni \mathcal{H} = \Sigma_n \oplus \mathcal{H}_n$$

$$\mathcal{H}_n \in |n;\beta\rangle \qquad (n = 0,1....N)$$

Method: Equation of Motion Phonon Method (EMPM)

Starting point

$$< n; \beta \,|[H, O^{\dagger}_{\lambda}]|\, n-1; \alpha > = (E_{\beta}^{(n)} - E_{\alpha}^{(n-1)}) < n; \beta \,|\, O^{\dagger}_{\lambda} |\, n-1; \alpha >$$

(LHS) (RHS)

Commutator expansion

Linearization

Eigenvalue Equation

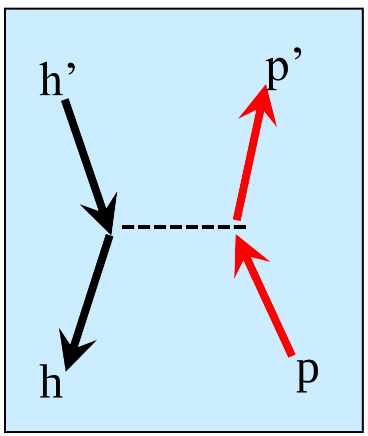
$$(AD)C = H\,C = E\,DC$$

$$(AD)C = H\,C = E\,DC$$

$$A = [\,E_{\lambda} + E_{\alpha}^{(n-1)}\,]\,\delta_{\lambda\lambda'}\,\delta_{\alpha\gamma} + \rho_{\lambda\lambda'}\,V\,\rho_{\alpha\gamma}^{(n-1)}$$

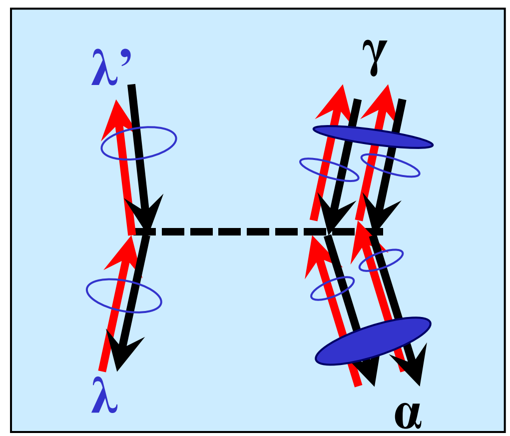
$D_n = \langle n-1;\ \alpha\,|O_{\lambda}\,O^{\dagger}_{\lambda'}|\ n-1;\ \alpha\rangle$ **overlap matrix**

TDA (n=1)



$$V_{ph'hp'}$$

MPEM (n=3)



$$\rho_{\lambda\lambda'}\,V\,\rho_{\alpha\gamma}^{(n-1)}$$

Diagonalization of the fulll H

Off-diagonal terms

$$< n; \beta \,|\, H \,|\, n-1; \alpha > = \text{ recursive formula}$$

$$< n; \beta \,|\, H \,|\, n-2; \alpha > = \text{ recursive formula}$$

Eigenvalue Equation

$$H\,|\Psi_\nu> = E_\nu\,|\Psi_\nu>$$

$$|\Psi_\nu> = \Sigma_{n\alpha}\; C_\alpha^{(\nu)}(n)\;\; |\, n;\alpha>$$

$$|n;\alpha> = \;\Sigma_\gamma\; C_\gamma^{(\alpha)}\, O^\dagger_\lambda\;\; |\, n-1;\gamma>$$

E.m. response

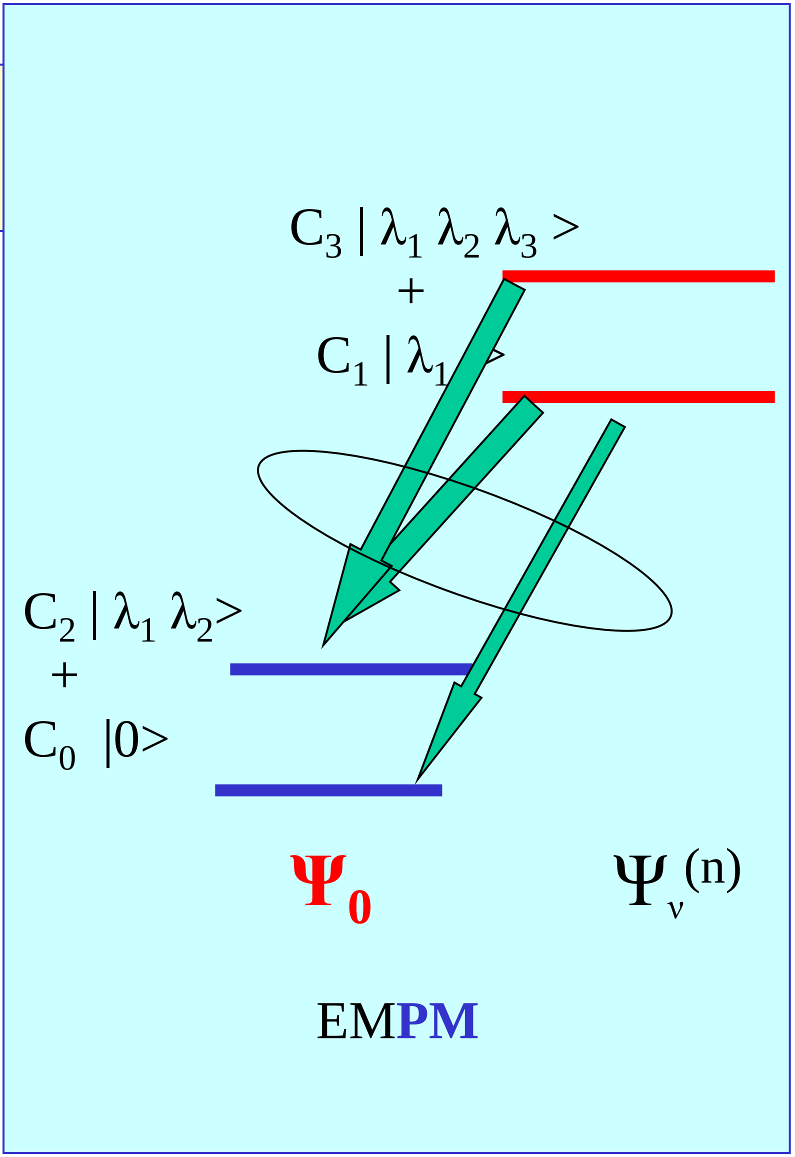
W.F.

$$|\Psi_\nu\rangle = \Sigma_{n\{\lambda\}} \; C_{\{\lambda\}}^{(\nu)}(n) \; | n;\{\lambda_1\lambda_2.\,\lambda_n\}\rangle$$

$$|\lambda\rangle = \Sigma_{ph} \; c_{ph}(\lambda) \, a^\dagger_p \, a_h|0\rangle$$

e.m. operator

$$\mathcal{M}_{\lambda\mu} = r^\lambda \; Y_{\lambda\mu}$$



Strength Function

$$S(E\lambda) = \Sigma \, B_n(E\lambda) \, \delta(E - E_n)$$

$$B_n(E\lambda) = |\langle\Psi_{n\nu}|| \mathcal{M}_\lambda ||\Psi_0\rangle|^2$$

^{16}O as theoretical lab

Structure of ^{16}**O**: A theoretical challenge

Pioneering work: First excited 0^+ as deformed 4p-4h excitations

G. E. Brown, A. M. Green, Nucl. Phys. 75, 401 (1966)

(TDA) IBM (includes up to 4 TDA Bosons)

H. Feshbach and F. Iachello, Phys. Lett. B 45, 7 (1973); Ann. Phys. 84, 211 (194)

SM up to 4p-4h and 4 ħω

W.C. Haxton and C. J. Johnson, PRL 65, 1325 (1990)

E.K. Warbutton, B.A. Brown, D.J. Millener, Phys. Lett. B293,7(1992)

No-core SM (NCSM) Huge space!!!

Symplectic No-core SM (SpNCSM) a promising tool for cutting the SM space

T. Dytrych, K.D. Sviratcheva, C. Bahri, J. P. Draayer, and J.P. Vary, PRL 98, 162503 (2007)

Self-consistent Green function (SCGF)

(extends RPA so as to include dressed s.p propagators and coupling to two-phonons)

C. Barbieri and W.H. Dickhoff, PRC 68, 014311 (2003);

W.H. Dickhoff and C. Barbieri, Pro. Part. Nucl. Phys. 25, 377 (2004)

EMPM : Exact implementation in ^{16}O

Hamiltonian

$H = H_0 + V = \Sigma_i h_{Nils}(i) + G_{bare}$ ($V_{BonnA} \Rightarrow G_{bare}$)

CM spuriosity free

$H \Rightarrow H + H_g$

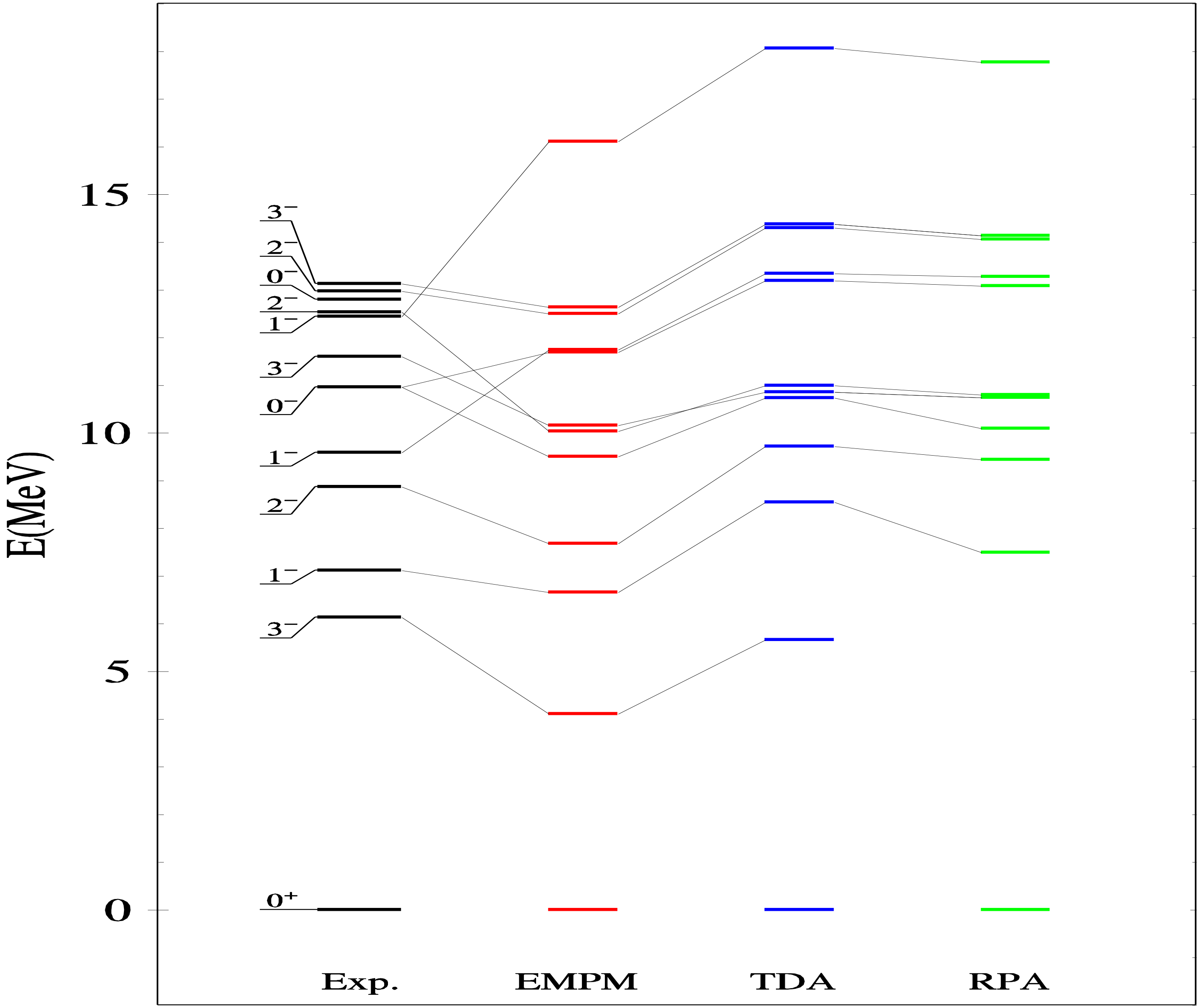
$H_g = g [P^2/(2Am) + (½) mA \omega^2 R^2]$

For g>>1 $E_{CM} >> E_{intr}$

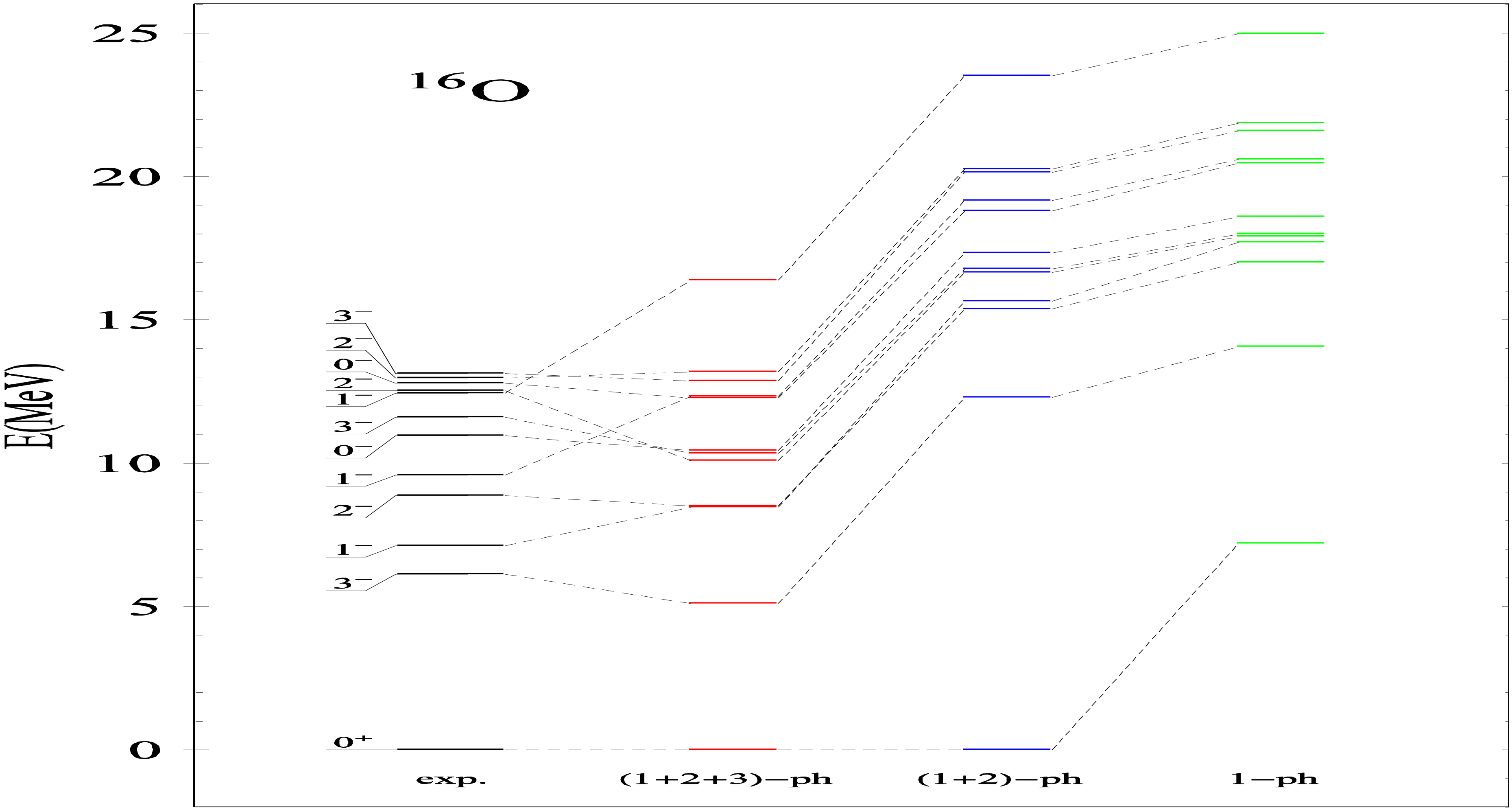
SM space

All particle-hole (p-h) configurations up to $3\hbar\omega$

Π⁻ Spectra (up to three phonons)



Π^- spectra (up to three phonons)

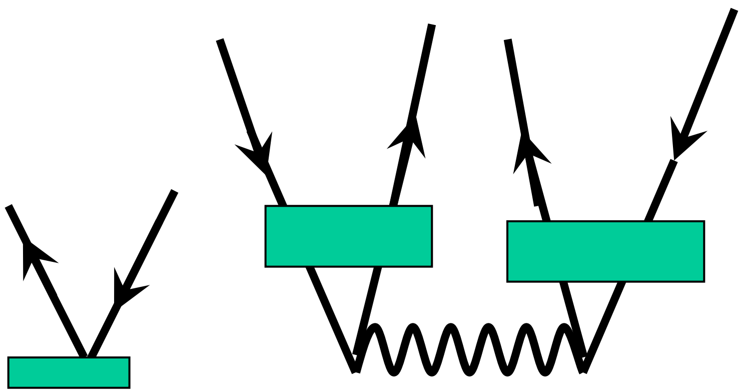


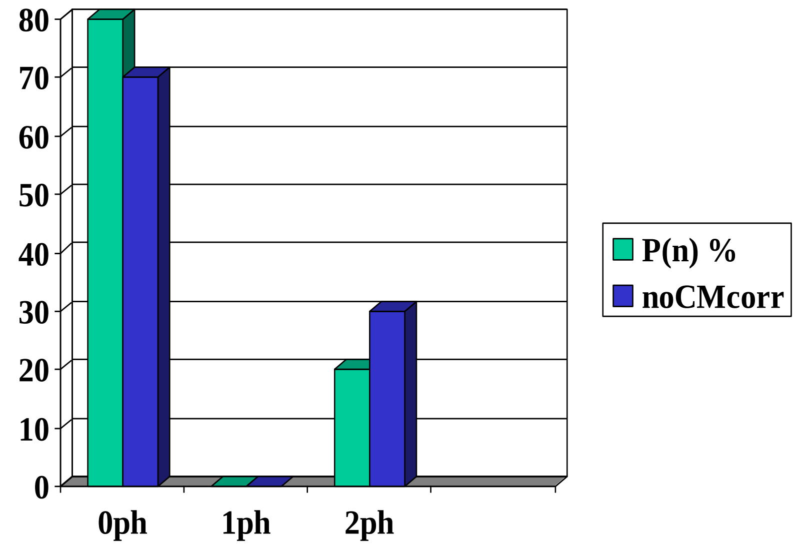
Ground state

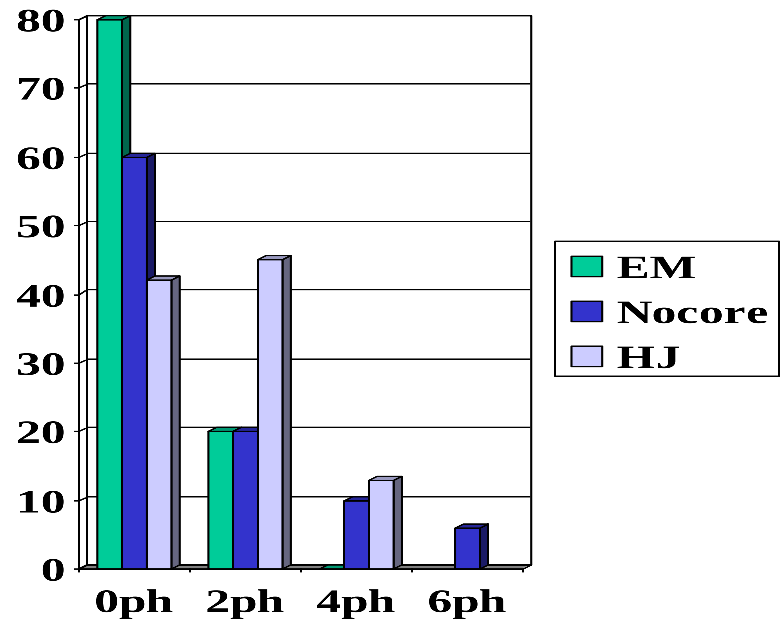
$$|\Psi_0\rangle = C_0^{(0)}\ |0\rangle$$

$$+\ \Sigma_\lambda\ C_\lambda^{(0)}\ |\lambda, 0\rangle$$

$$+\ \Sigma_{\lambda_1\lambda_2}\ C_{\lambda_1\lambda_2}^{(0)}\ |\lambda_1\ \lambda_2, 0\ \rangle$$



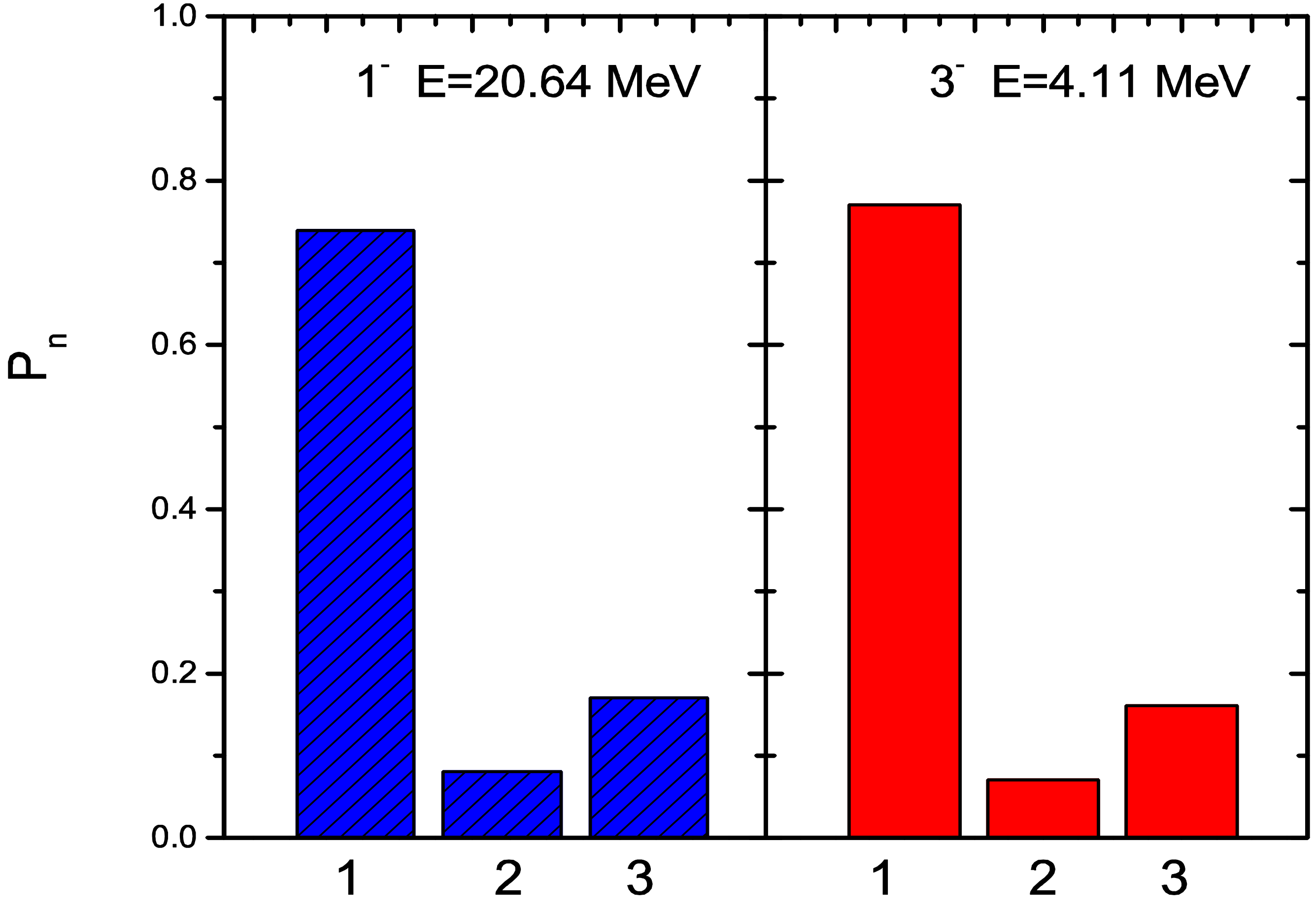




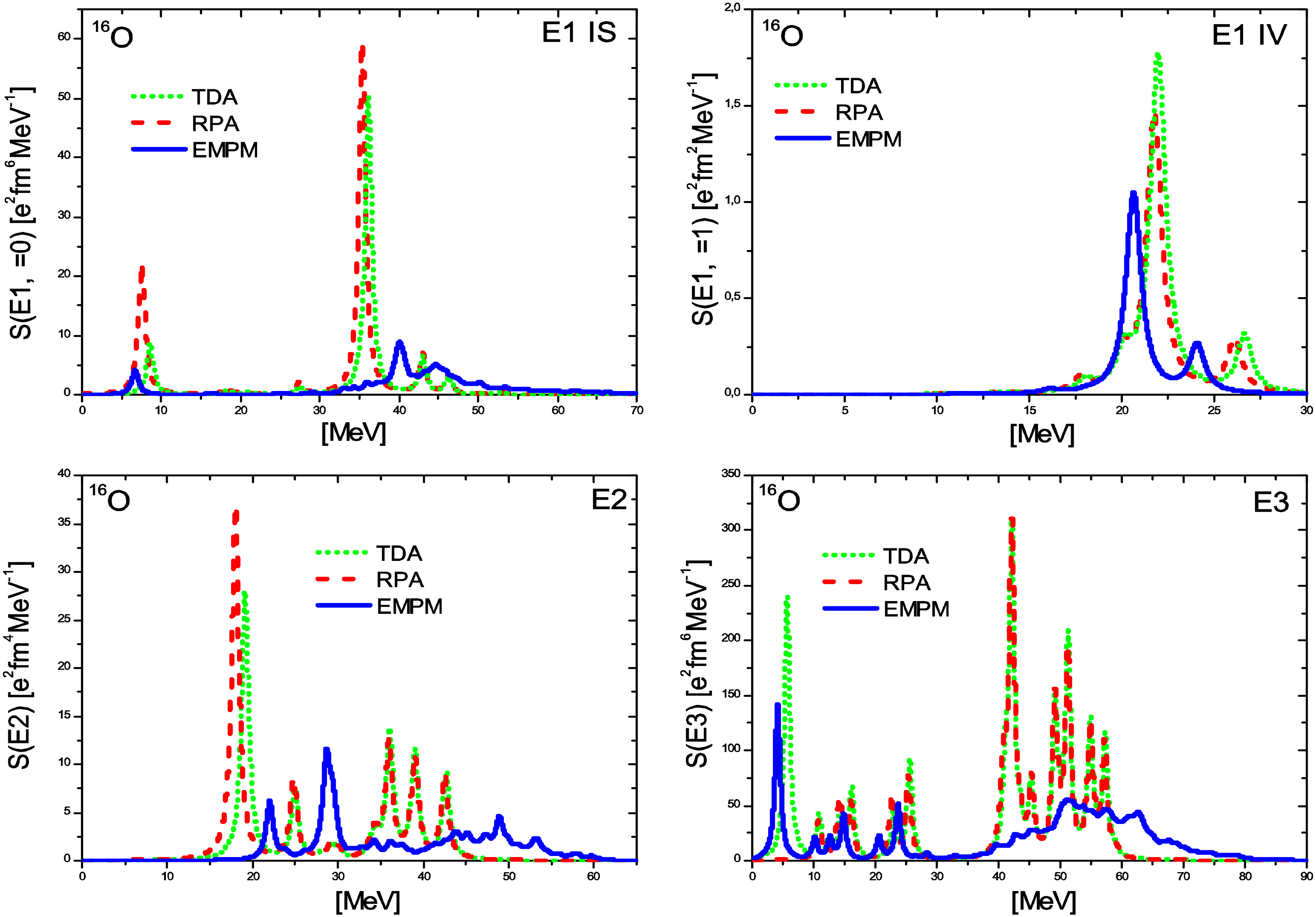
$$1 = \langle\ \Psi_0|\Psi_0\rangle = P_0 + P_1 + P_2$$

Phonon components

$$P_n = |\langle n|\Psi\rangle|^2$$

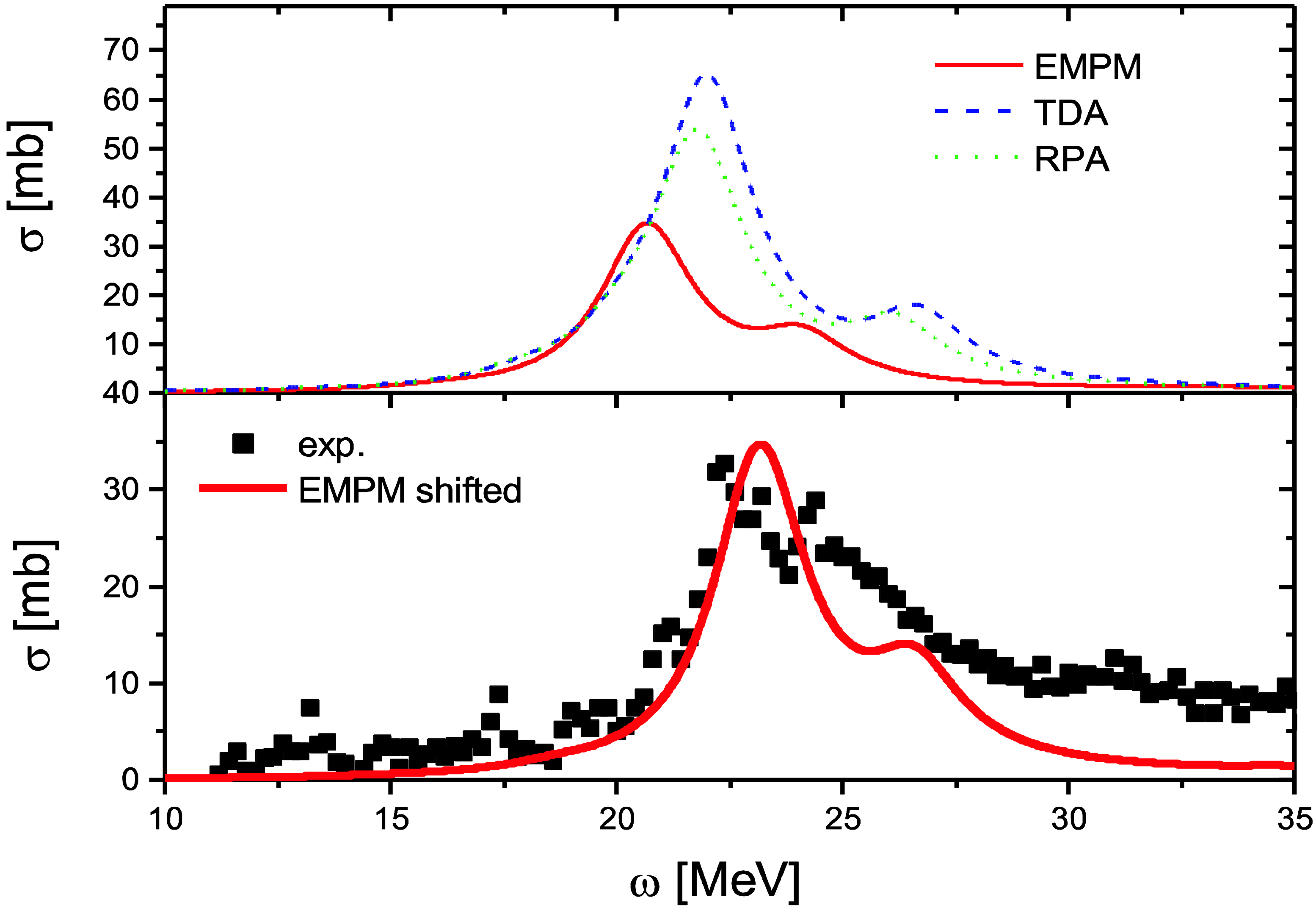


Eλ response



16O
E1 IS
TDA
RPA
EMPM
S(E1, =0) [e2fm6MeV-1]
[MeV]
16O
E1 IV
TDA
RPA
EMPM
S(E1, =1) [e2fm2MeV-1]
[MeV]
16O
E2
TDA
RPA
EMPM
S(E2) [e2fm4MeV-1]
[MeV]
16O
E3
TDA
RPA
EMPM
S(E3) [e2fm6MeV-1]
[MeV]

IV DGR



EMPM
TDA
RPA
σ [mb]
70
60
50
40
30
20
10
40
exp.
EMPM shifted
σ [mb]
30
20
10
0
10
15
20
25
30
35
ω [MeV]

Concluding remarks

- QPM analysis

- Heavy spherical nuclei: The multiphonon collective scheme (as in IBM) valid near N=50. In proximity of N=82, shell effects induce pronounced fragmentation (anharmonicity)

- 0^+ states in deformed nuclei: Mainly one-phonon pairing vibrational

- 4^+ states in Os: admixtures of one and two phonons

The EMPM (work in progress)

Future steps

- Upgrading the method so as to include up to four phonons (at least). This task is in the final stage.
- Extend the method to open shell nuclei. Project at an advanced stage.

THANK YOU