Role of Complex Configurations in Nuclear Spectroscopy

N. Lo Iudice
Università di Napoli Federico II

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A QPM study of low-lying spectra in

- **Spherical heavy nuclei**

in collaboration with Ch. Stoyanov (Sofia)

-- **Deformed heavy nuclei**

in collaboration with A.V. Sushkov (Dubna)

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

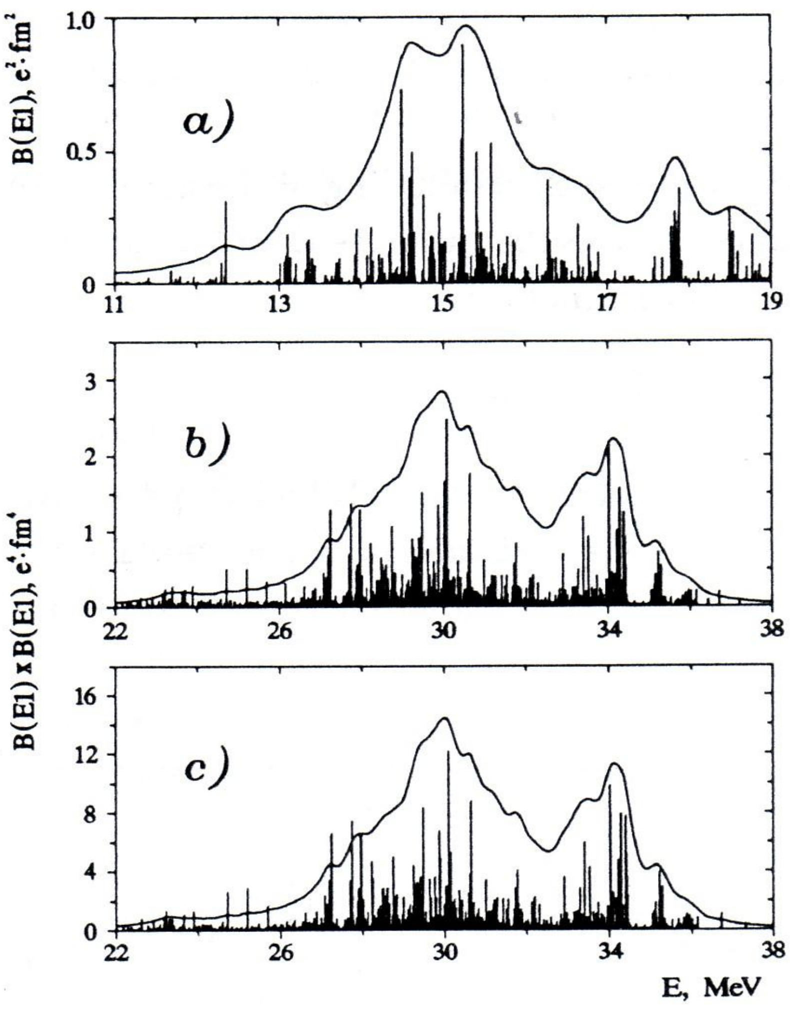
$$D \times D|0>$$

and

triple

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

dipole giant resonances



Multiphonon excitations: Exp. evidence

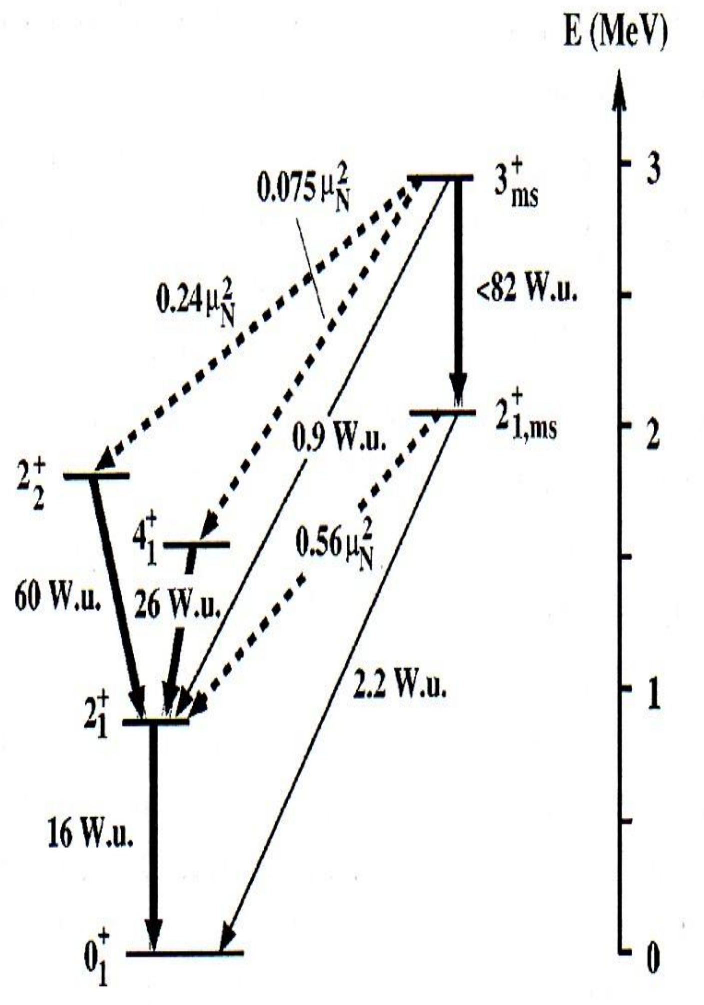
** Low-energy

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))



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

A brief outline

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

$$V_{pp} = \Sigma_\lambda \; G_\lambda \, P_\lambda^\dagger \, P_\lambda \qquad P_\lambda^\dagger = \Sigma_\lambda \, f^\lambda_{ij} \, (a_i^\dagger \times a_j^\dagger)^\lambda$$

$$V_{ff} = \Sigma_\lambda \; \kappa_\lambda \, F_\lambda^\dagger \, F_\lambda \qquad F_\lambda^\dagger = \Sigma_\lambda \, f^\lambda_{ij} \, (a_i^\dagger \times a_j)^\lambda$$

1° step: From particle to quasiparticle

$$\{a^\dagger a\} \Rightarrow \{\alpha^\dagger \alpha\}$$

⇓

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

(ph) (qp)

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

2nd step: From quasiparticles to RPA phonons of multipolarity λ

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

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

3° step: From particle to phonon Hamiltonian

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

↓

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

↓

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

Spherical Nuclei: π-ν Symmetric and MS states

Symmetric

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

MS

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

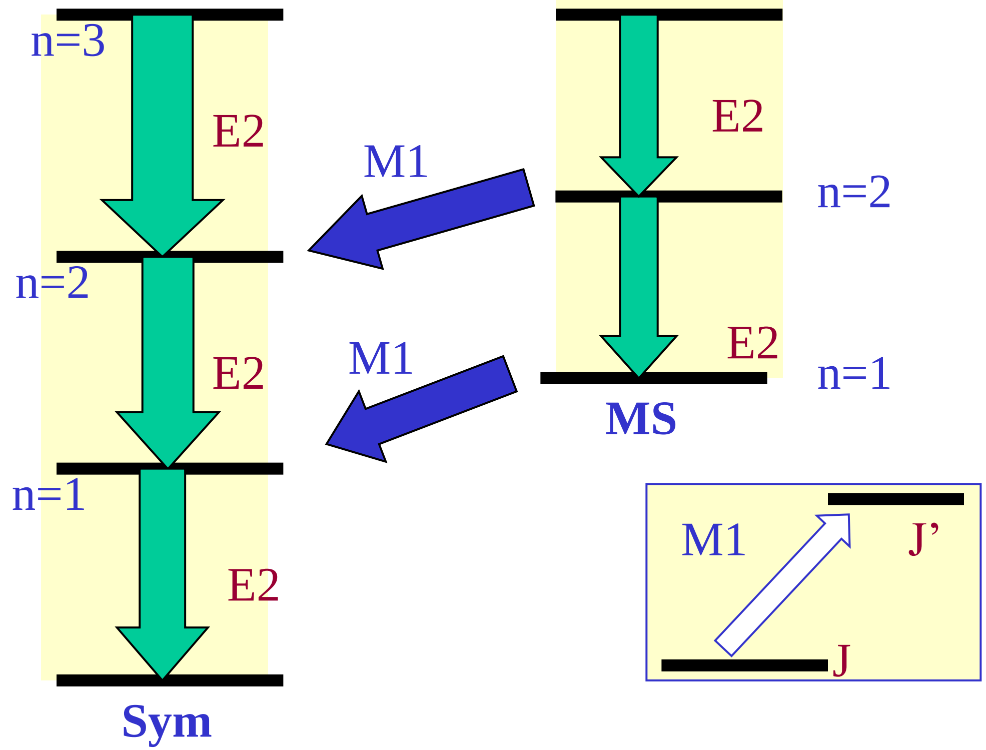
Signature: Transitions

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

symmetry preserving (ΔF=0)

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

symmetry changing (ΔF=1)



Scissors multiplet

$S\ |n, \nu\rangle_S = (J_p - J_n)\ Q_S^n\ |0\rangle$

$\propto [(Q_p - Q_n)\ (Q_p + Q_n)^{(n-1)}]|0\rangle$

$\propto |n, \nu\rangle_{MS}$

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

Preliminaries: Testing the isospin nature of the QRPA 2^+ states through the ratio

$$B(2^+)_{RPA} = \left| \frac{\langle 2^+|(Q_p - Q_n)|0\rangle}{\langle 2^+|(Q_p + Q_n)|0\rangle} \right|^2$$

1. $B(2^+) < 1 \rightarrow |2^+\rangle$ **isoscalar** ($\Delta T=0$)

2. $B(2^+) > 1 \rightarrow |2^+\rangle$ **isovector** ($\Delta T=1$)

B(2⁺) is very sensitive to the ratio G_2/κ_2

In ^{136}Ba

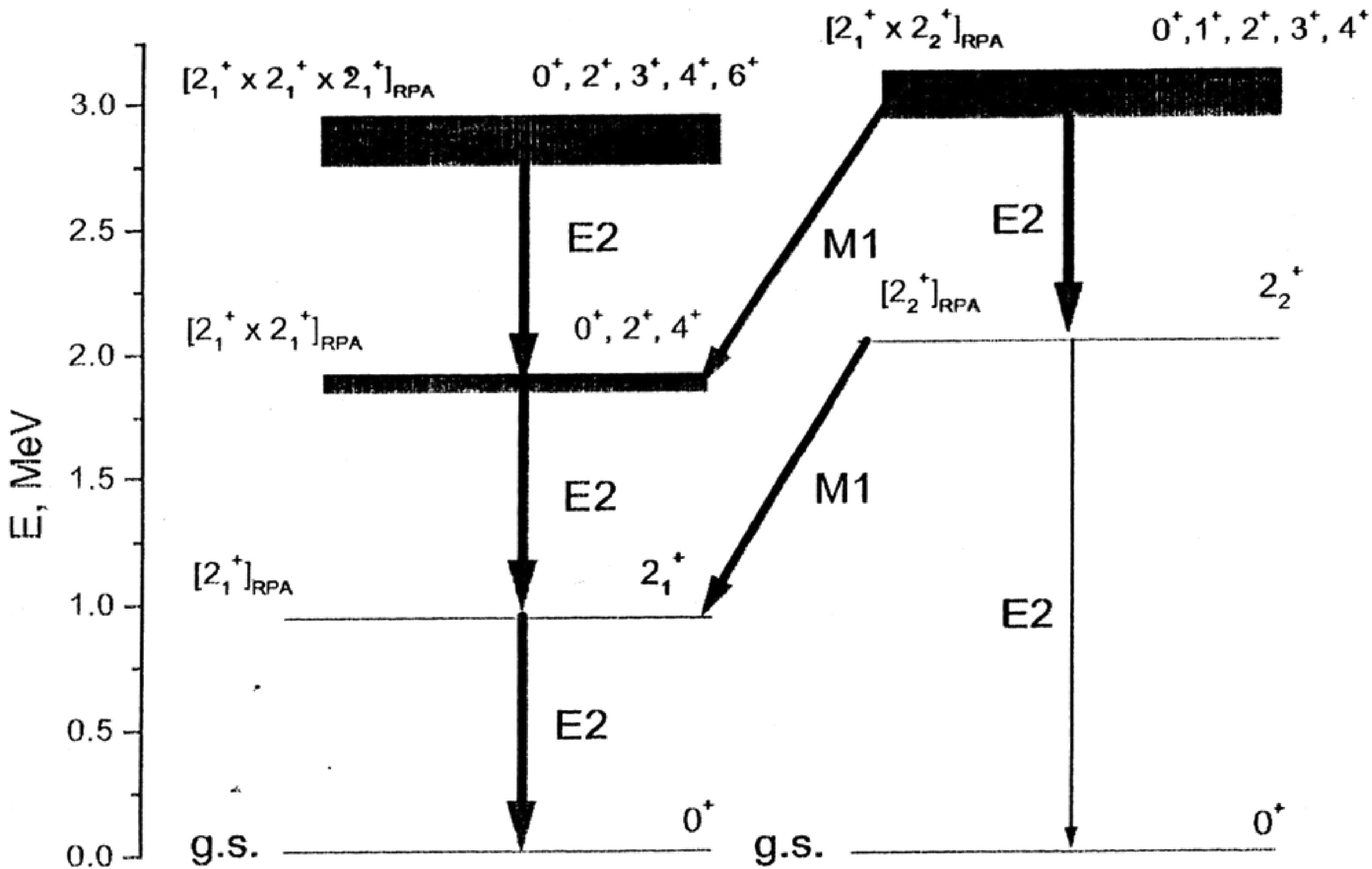
$\frac{G^{(2)}}{\kappa_0^2}$	$B(E2)_{RPA}$ g.s.$\rightarrow 2^+_{iv}$ $[e^2b^2]$	$B(M1)_{RPA}$ $2^+_{iv} \rightarrow 2^+_{is}$ $[\mu_N^2]$	$B(2^+_{iv})$
0	0.0032	0.042	0.58
0.85	0.011	0.24	22.6

Low-lying states in ^{94}Mo:

Energies and phonon structure

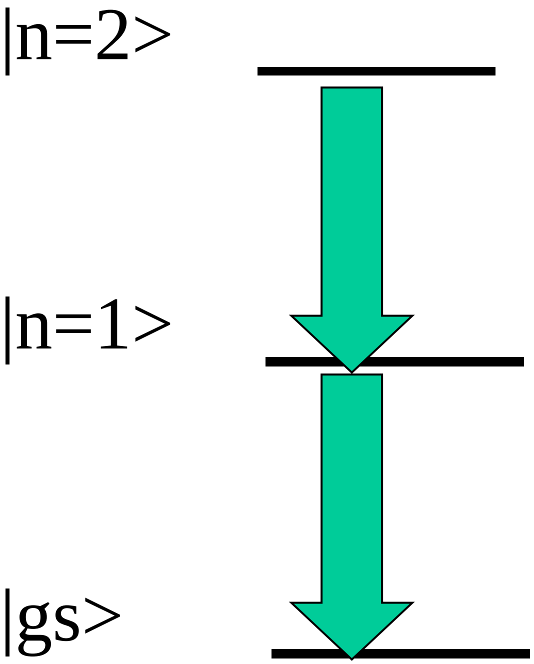
State T	J^π	E (keV) EXP	QPM	Structure,%
	$2^+_{1,\mathrm{is}}$	871	860	$93\%[2^+_{\mathrm{is}}]_{\mathrm{RPA}}$
IS	$2^+_{2,\mathrm{is}}$	1864	1750	$82\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{is}}]_{\mathrm{RPA}}$
	$4^+_{1,\mathrm{is}}$	1573	1733	$82\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{is}}]_{\mathrm{RPA}}$
	$1^+_{1,\mathrm{iv}}$	3129	2880	$90\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
	$2^+_{1,\mathrm{iv}}$	2067	1940	$95\%[2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
	$2^+_{2,\mathrm{iv}}$	2393	2730	$27\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
	$2^+_{3,\mathrm{iv}}$	2740	3014	$59\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
IV	$4^+_{1,\mathrm{iv}}$		3120	$64\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
	$3^+_{1,\mathrm{iv}}$	2965	2940	$87\%[2^+_{\mathrm{is}} \otimes 2^+_{\mathrm{iv}}]_{\mathrm{RPA}}$
	1^+_2		3550	$40\%[1^+_1]_{\mathrm{RPA}}$

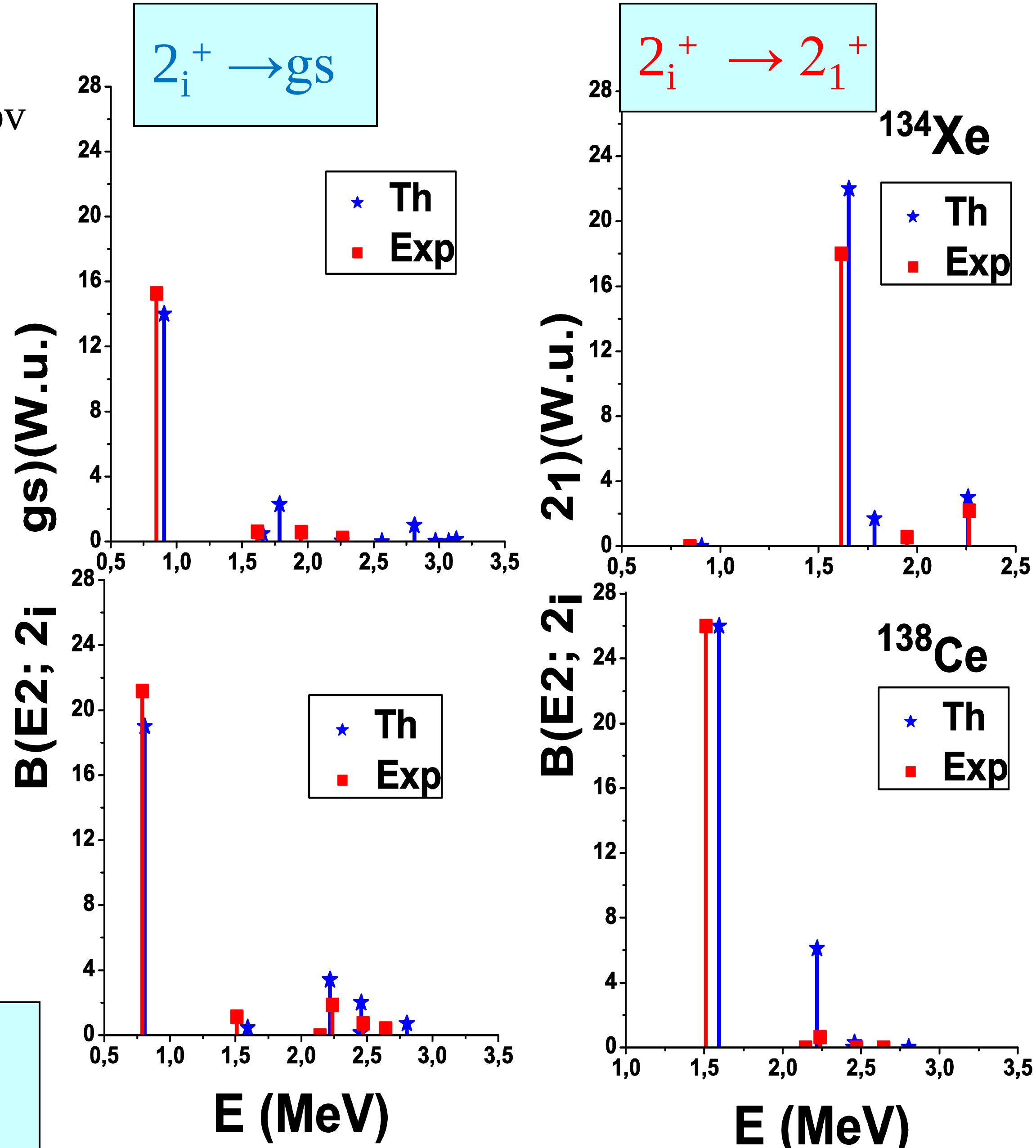
^{94}Mo level scheme.



N=80 isotones

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





E2 Transitions

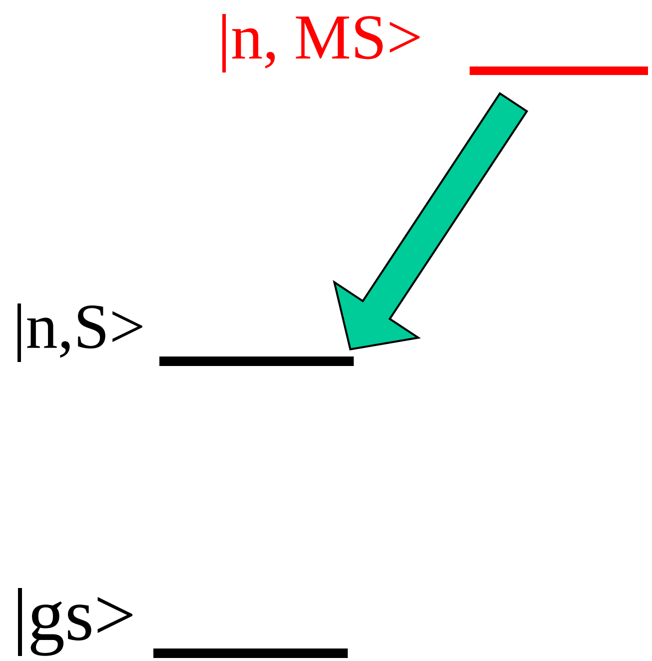
(ΔF=0, Δn =1)

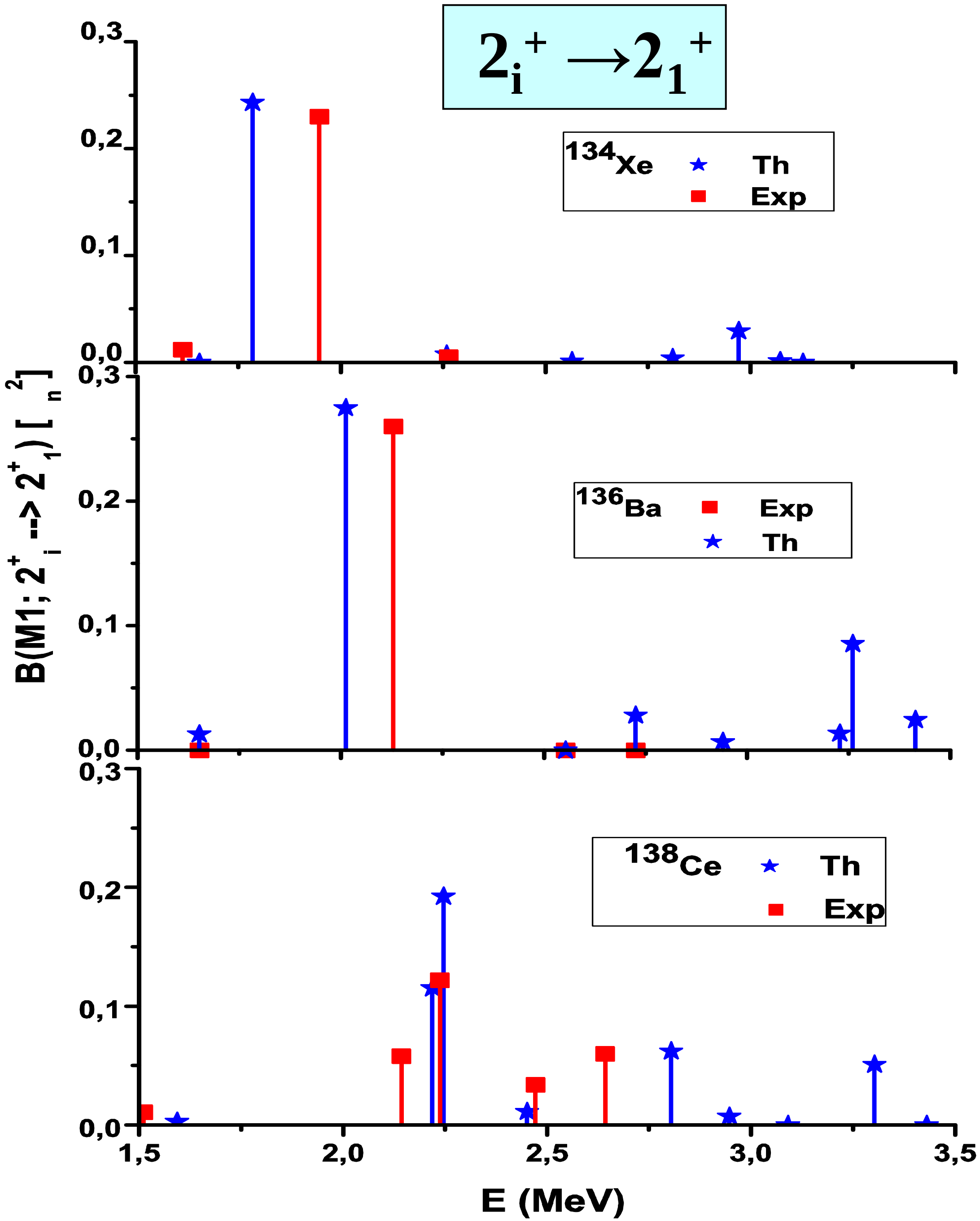
N=80

M1 Transitions

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

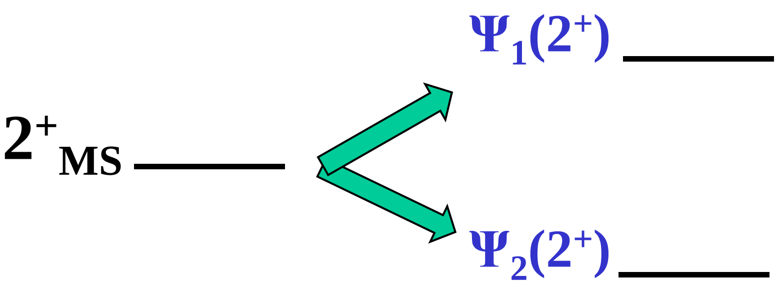
QPM versus EXP

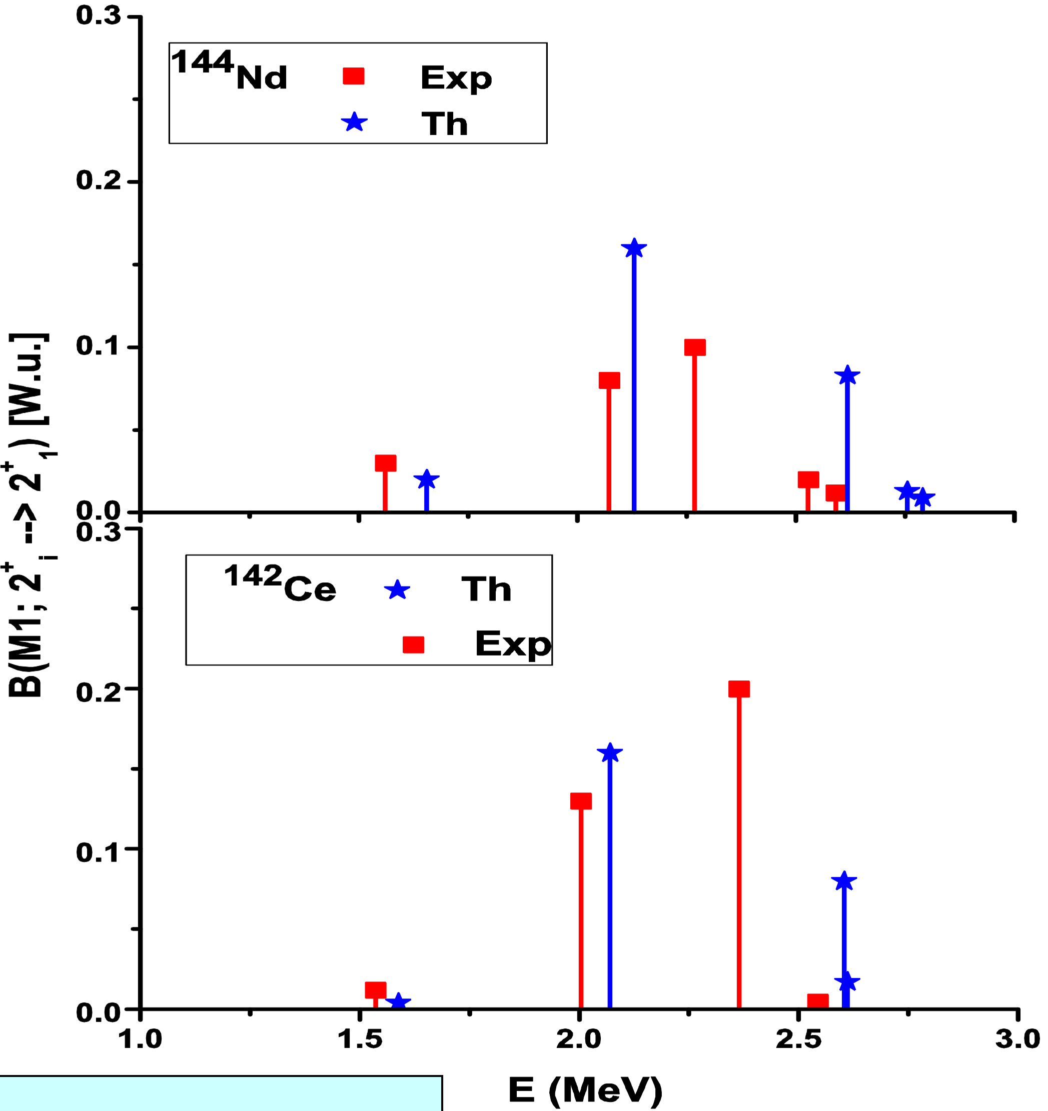




Splitting of B(M1)
in N=84 isotones

N. L. Ch. Stoyanov N. Pietralla PRC 80(2009)





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))

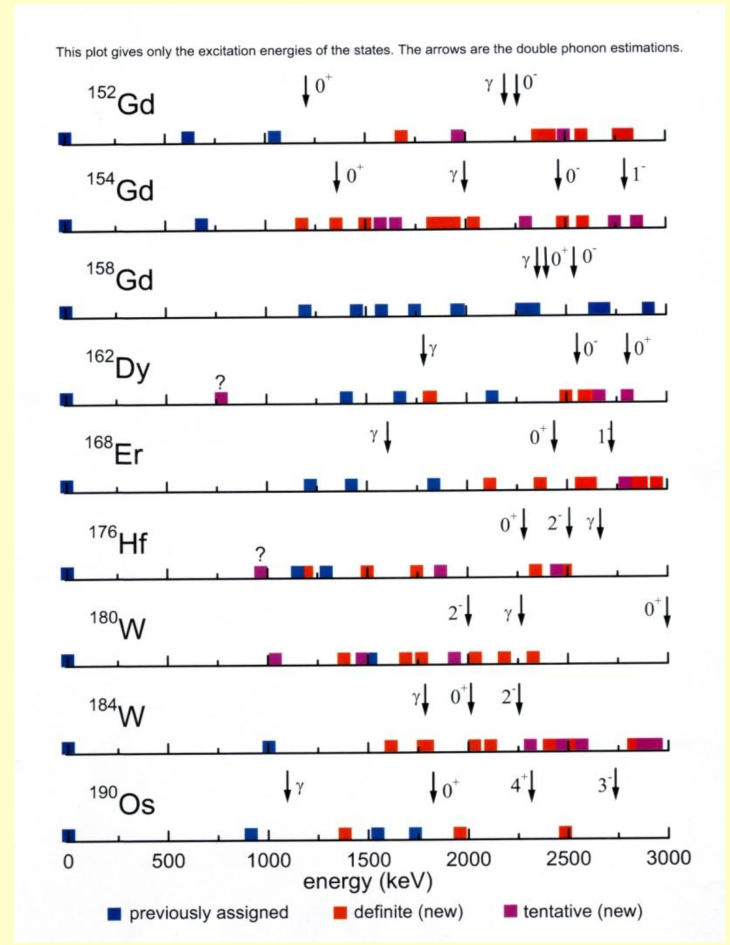
^{228}Th, ^{230}Th and ^{232}U

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)

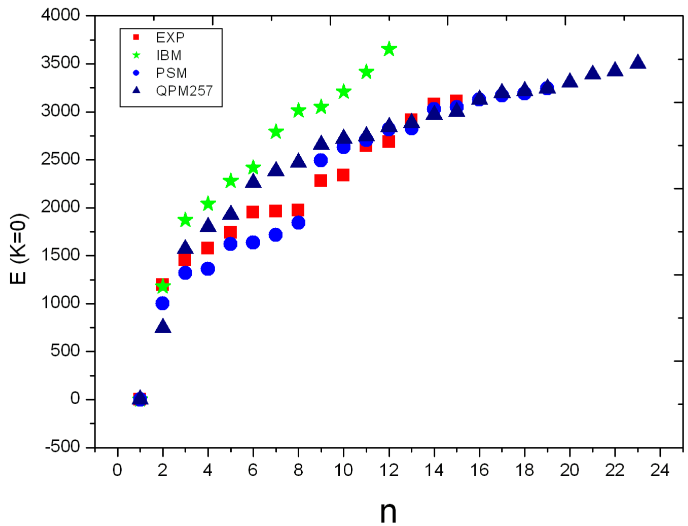


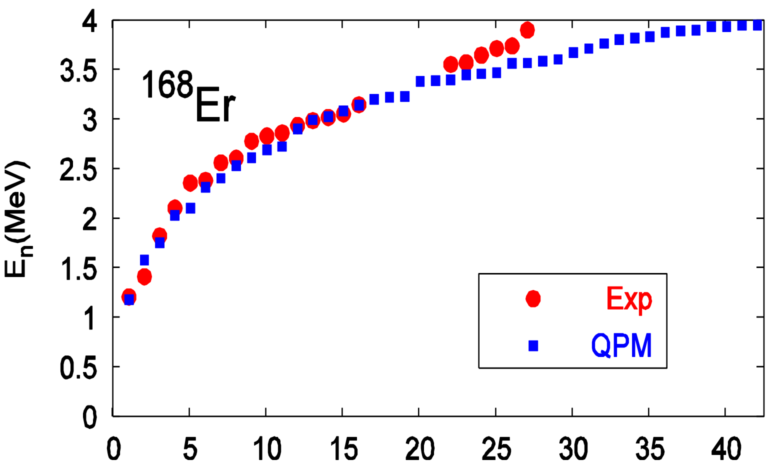
Systematic

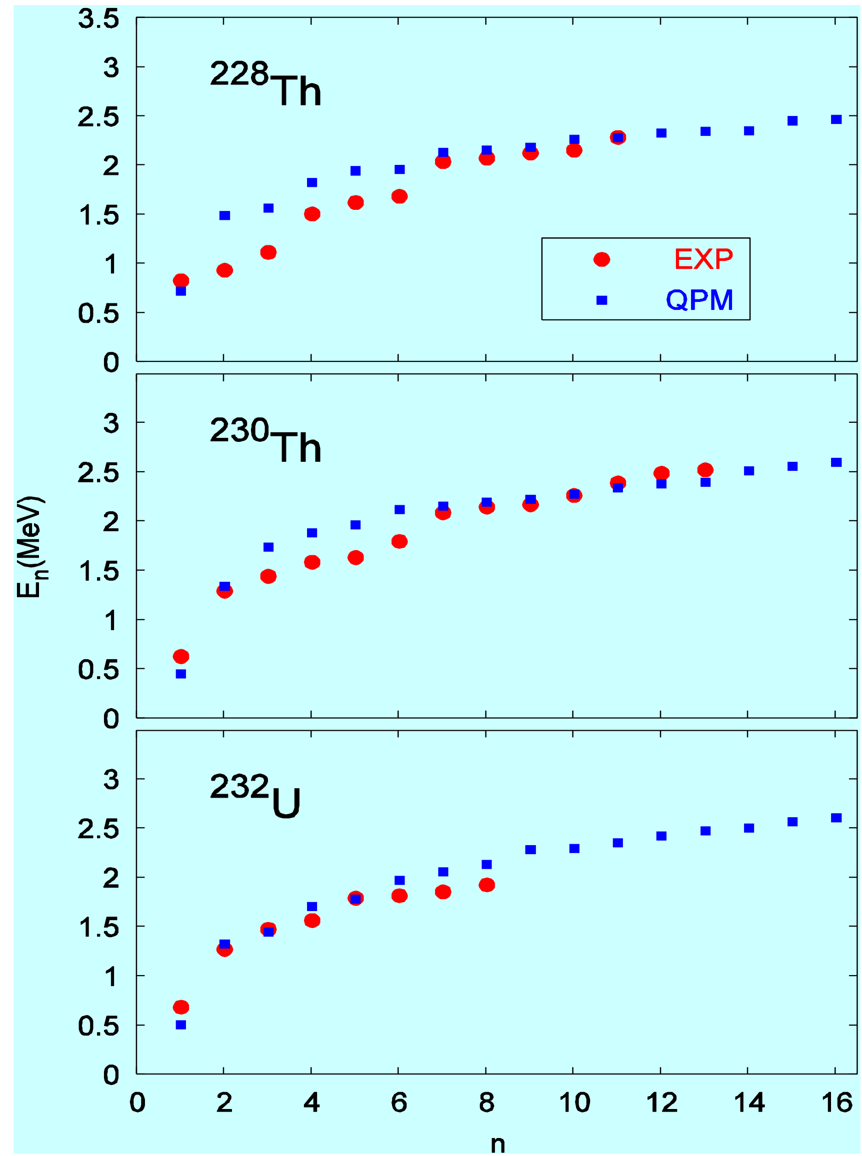
D. A. Meyer et al., PRC 74, 044309 (2006) and references therein

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

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







Nature of the 0^+ :Quadrupole collective (β-band)?

$|K^\pi=0^+\rangle$ ~ $Q_0\,|0\rangle$ No !!

$B(E2, 0^+ \rightarrow 2_g^+) \ll B_{vib}(E2)$

~ $\langle 0\,|Q_0^2|0\rangle$ ~ 33 w.u.

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

$B(E0) \ll B_{vib}(E0)$ ~

$\langle 0\,|(r^2)^2|0\rangle / \langle 0|r^2|0\rangle^2$

~ 85 ÷ 230 (10-3)

J. L. Wood et al. NPA651 (1999) 323

But we need more experimental information

Nature of the 0^+ : Pairing vibration?

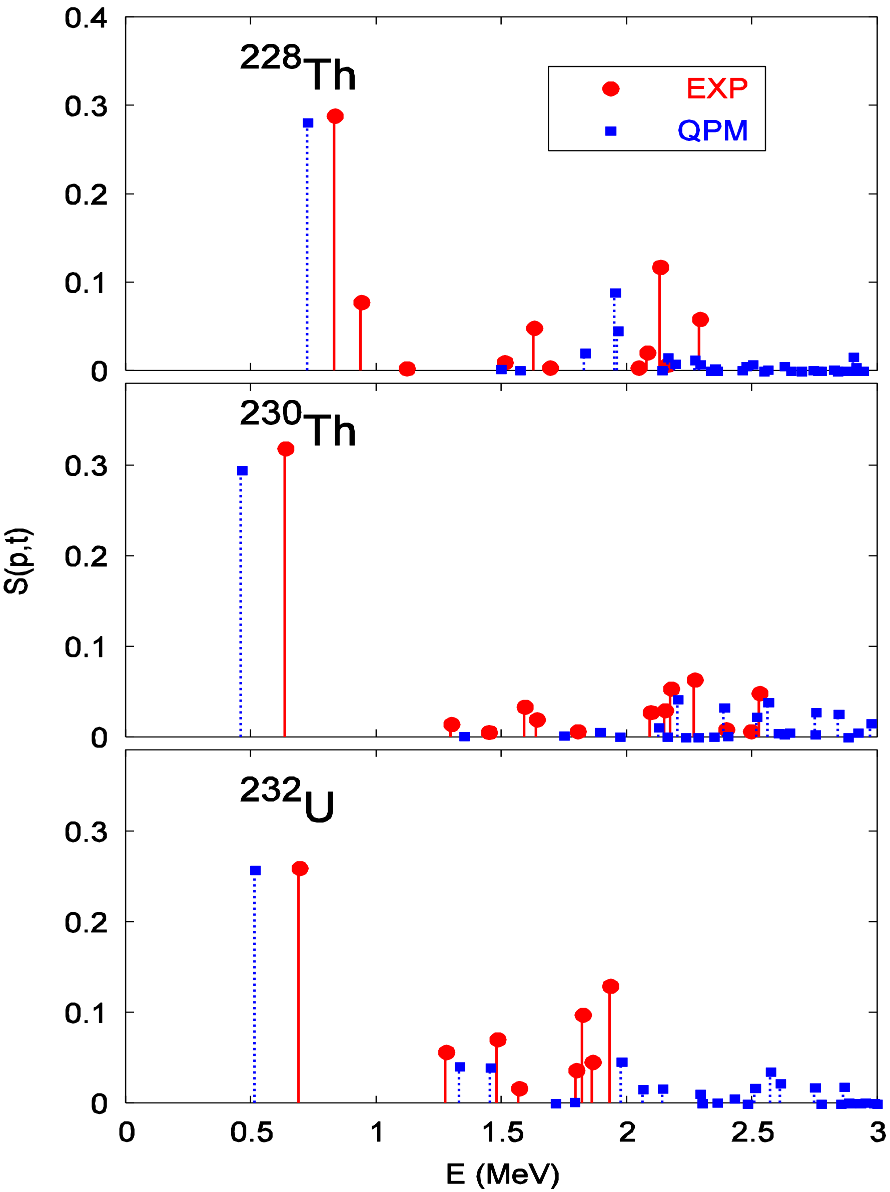
$$\langle 0 | P_0^2 | 0 \rangle \sim |\langle n | P_0 | 0 \rangle|^2$$

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

Normalized (p,t) spectroscopic factors

$$S_n(p,t) = [\langle n|P_0|0\rangle / \langle 0|P_0|0\rangle]^2$$

S(p,t) and pairing collectivity



RPA w.f.

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

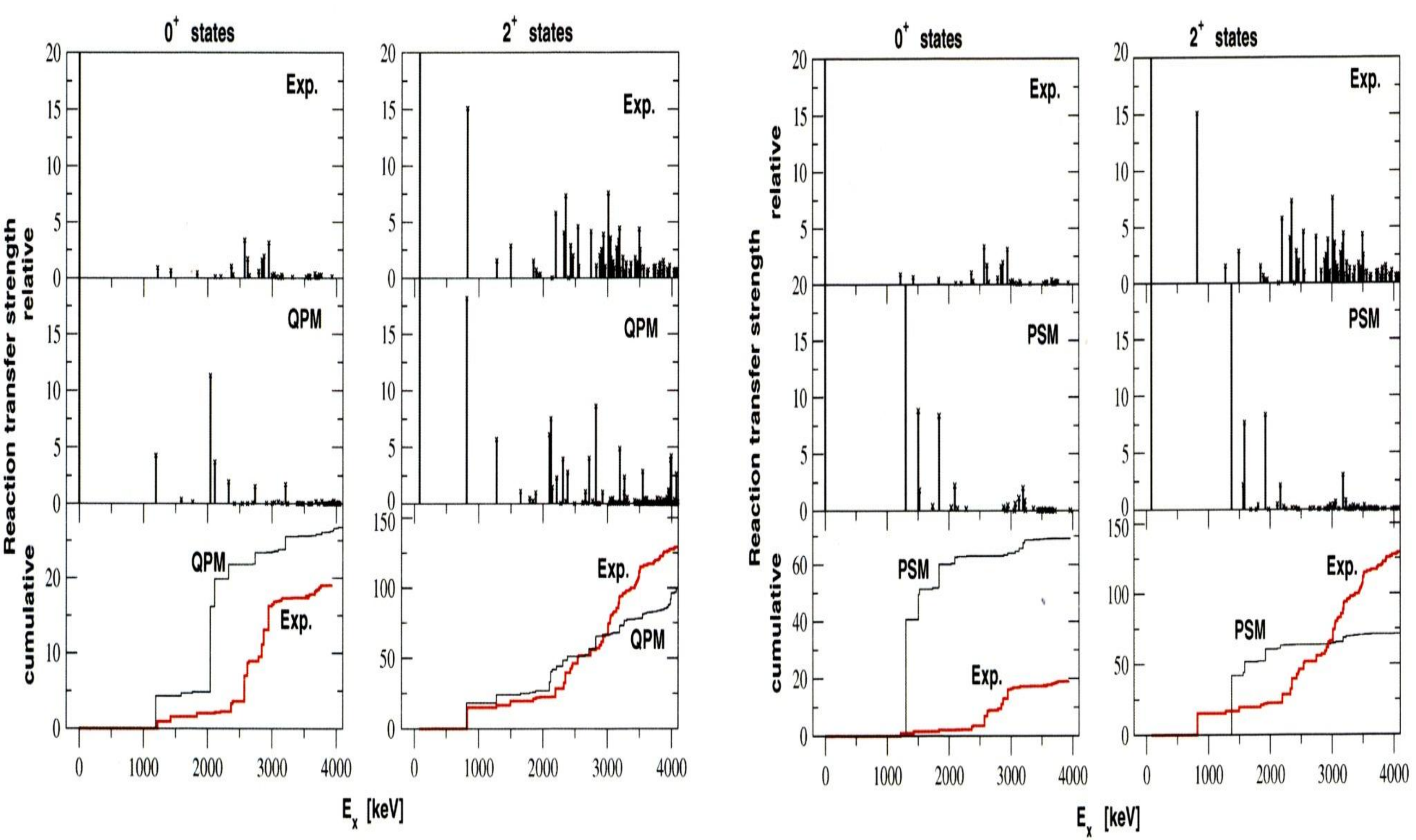
Pairing acts **coherently** only in the **lowest RPA 0+** !!!

Fragmentation due to

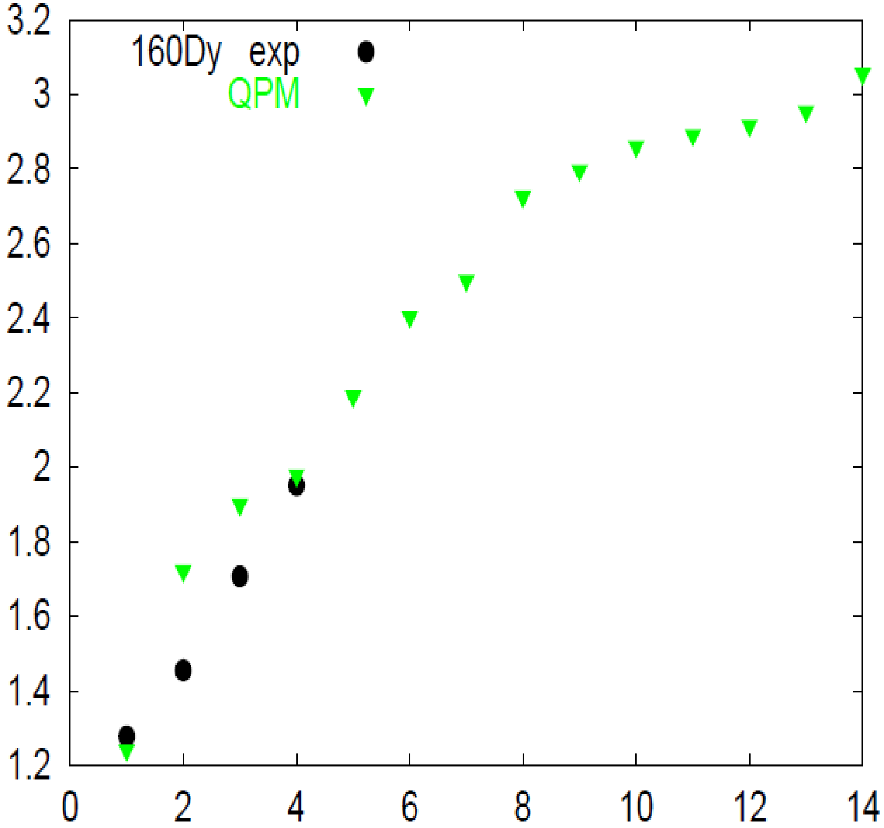
i) s.p. decay (Landau damping)

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

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



0^+ in transitional nuclei: ^{160}Dy

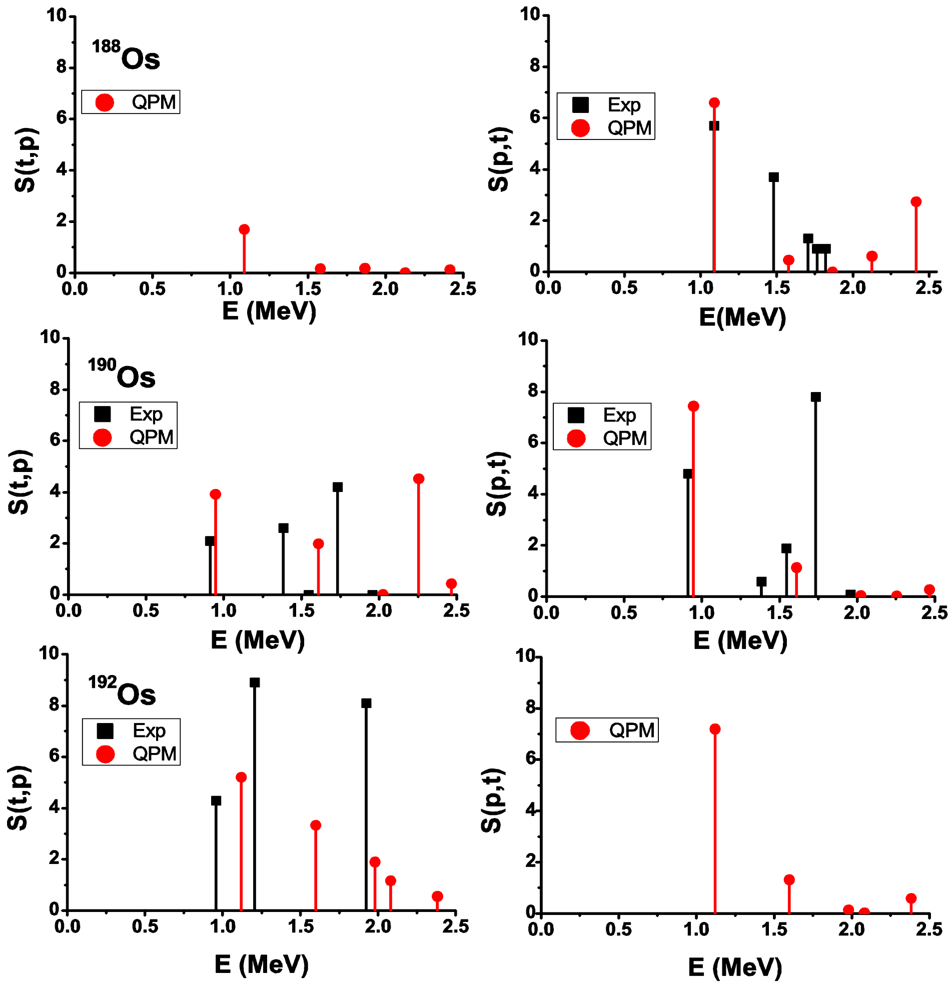


$S(pt)$ for 1279.95 keV state

Exp	Calc
0.15	0.18

0^+ in γ-soft nuclei:Os isotopes

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



Evolution toward γ softness (from A=188 to A=192)

-Increasing strenghts S(t,p) and S(p,t)

-Increasing complexity of $|\Psi_0>$

***Fragmentation of $|\Psi_0>$**

$|\Psi_0> \sim c_1 |(20)_1> + c_2 |(20)_2> + .. +.. c_{22}|(22)_1,(22)_1>$

**** dominance of π-pairing in $|(20)_1>$ and of ν-pairing in others**

Dominant two-phonon configurations

^{158}Gd	MeV
$31 \otimes 31$	1.96
$44 \otimes 44$	2.9

^{168}Er	MeV
$22 \otimes 22$	2.8
$4^- \otimes 4^-$	2.6

^{160}Dy	MeV
$22 \otimes 22$	1.7
$32 \otimes 32$	2.5
$4^- \otimes 4^-$	3.3
$44 \otimes 44$	3.6

^{190}Os	MeV
$22 \otimes 22$	0.94
$33 \otimes 33$	2.5
$32 \otimes 32$	2.8
$44 \otimes 44$	3.6

Nature of 0^+ states

multiphonon excitations ? NO (in general)

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

Elementary one-phonon excitations ? Yes

Collective β**-vibrations?** **No!**

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

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

4^+ state in Os isotopes

Double-γ ? (C.Y. Wu et al. PRC 64 (01))

– $E_4 \sim 2\ E_\gamma$

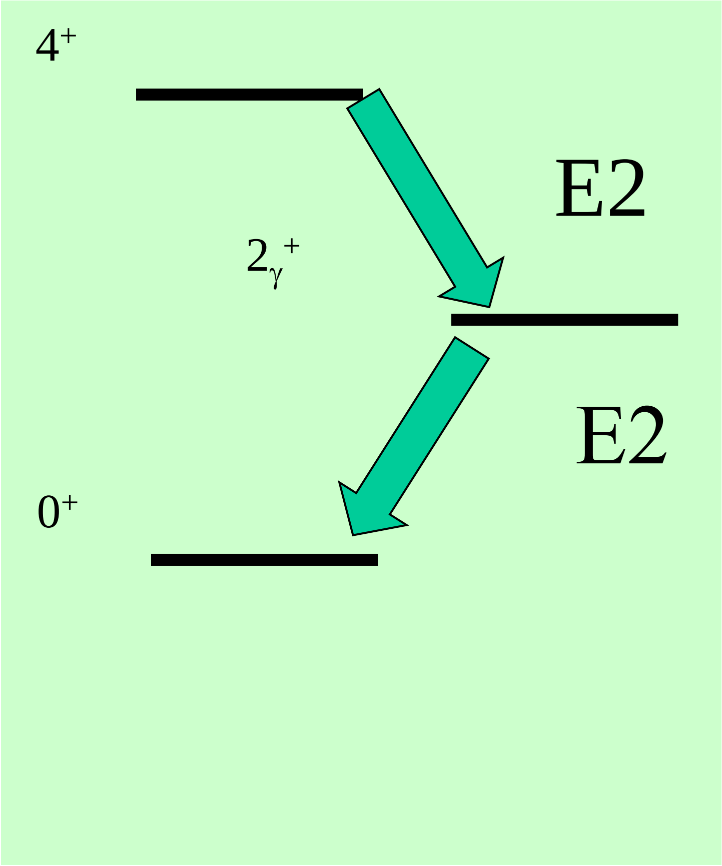
$R_4(E2) = B(E2, 4^+ \rightarrow 2^+)/B(E2, 2^+ \rightarrow 0^+) \sim 2$

$$|\Psi_4> \sim\ |\gamma\gamma>$$

with

$$|c(n=1)|^2 < 25\ \%$$

one-phonon hexadecapole admixture



4^+ state in Os isotopes

Hexadecapole one-phonon? (D. G. Burke PRC 66 (02))

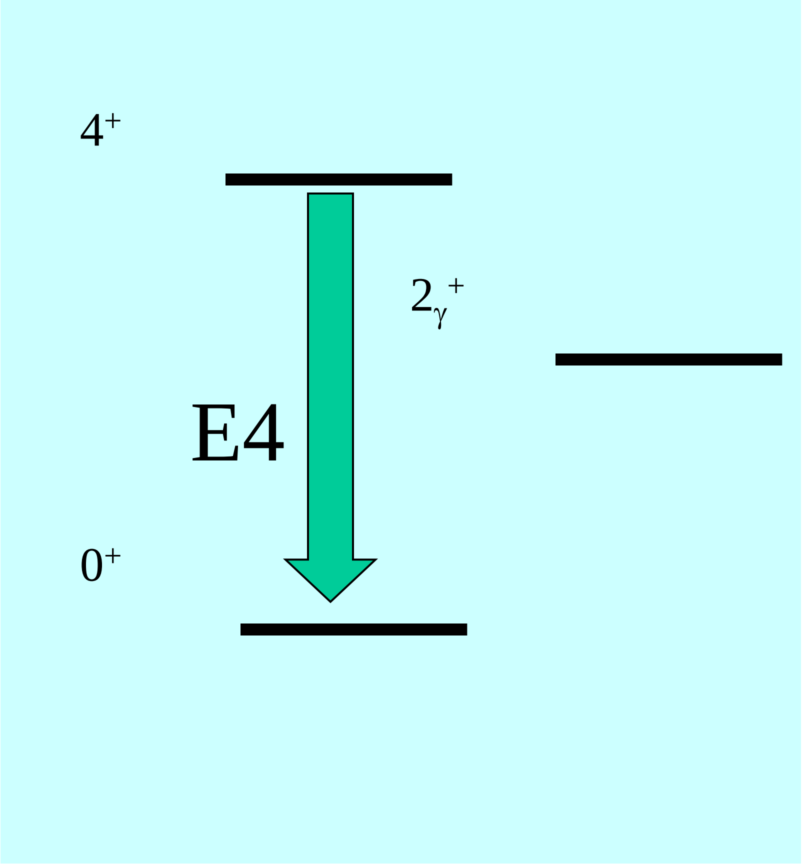
-B(E4, K=4 → 0) large

- From (t, α) (d,^{3}He)

large admixtures of

$5/2^+[402]_\pi + 3/2^+ [402]_\pi$

$|\Psi_4\rangle \sim |n=1,4+\rangle$



4^+ state in Os isotopes

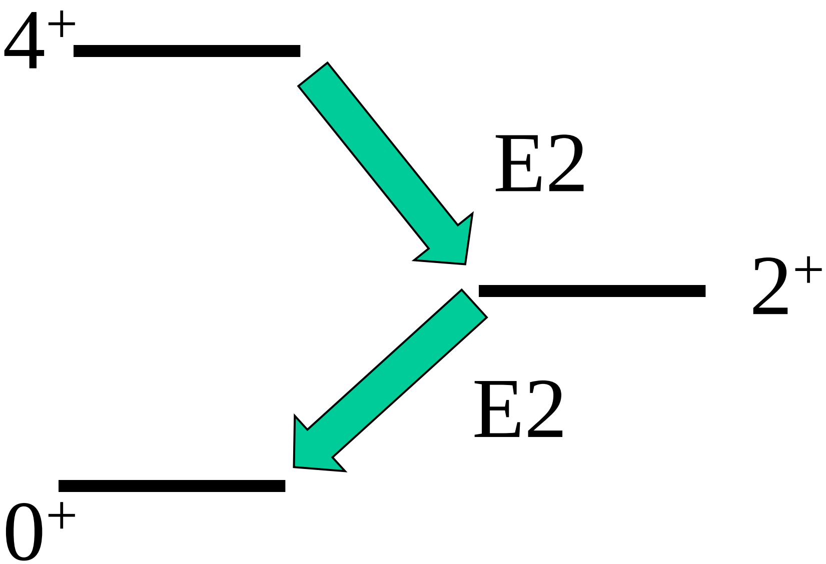
N. Lo Iudice and A. V. Sushkov, PRC 78, 054304 (2008).

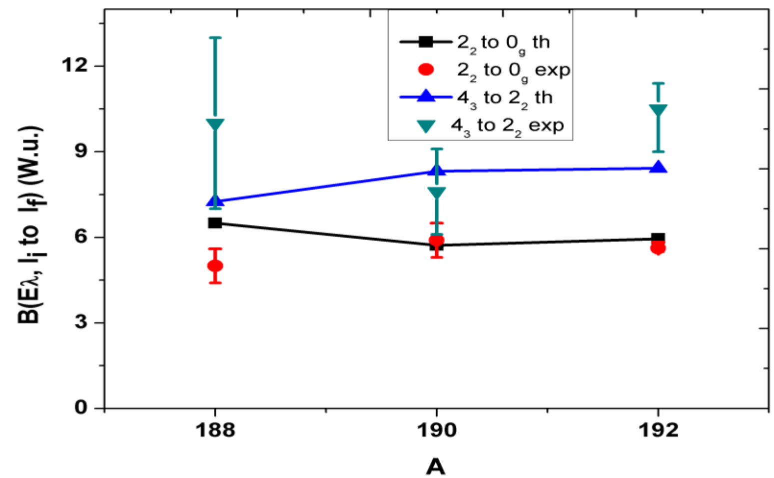
QPM

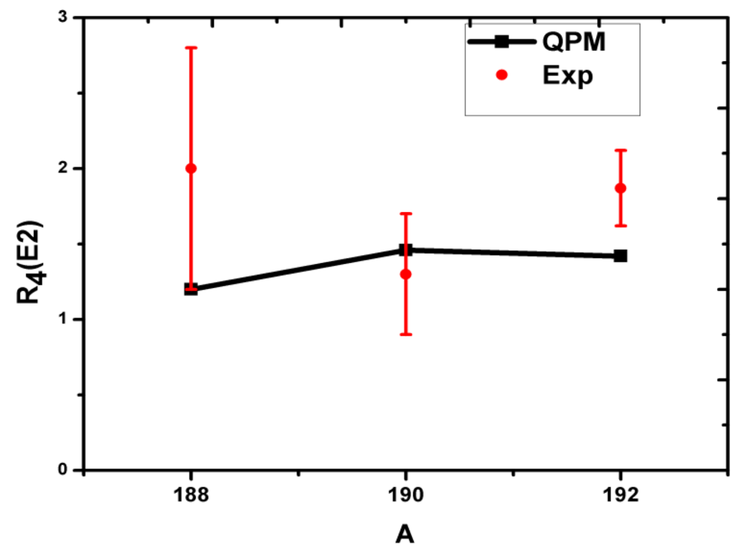
$$|\Psi_4\rangle \sim \quad 0.60\ |n=1, 4^+\rangle$$

$$+ \quad 0.35\ |n=2, \gamma\gamma\rangle$$

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



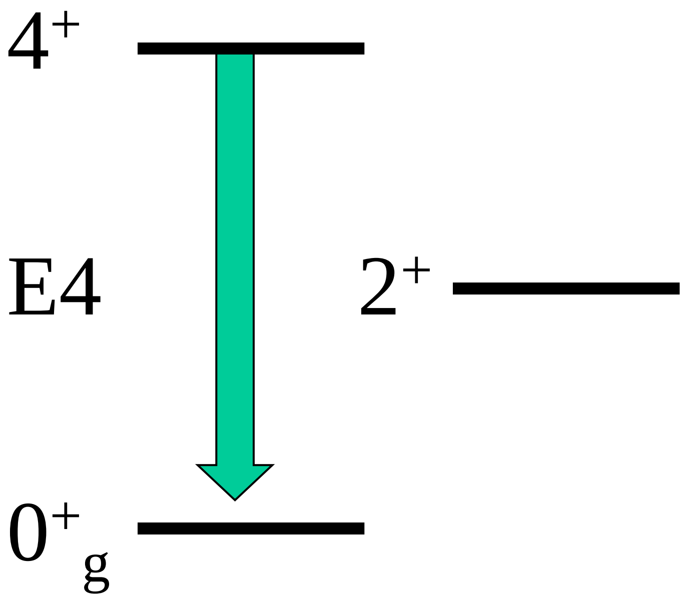


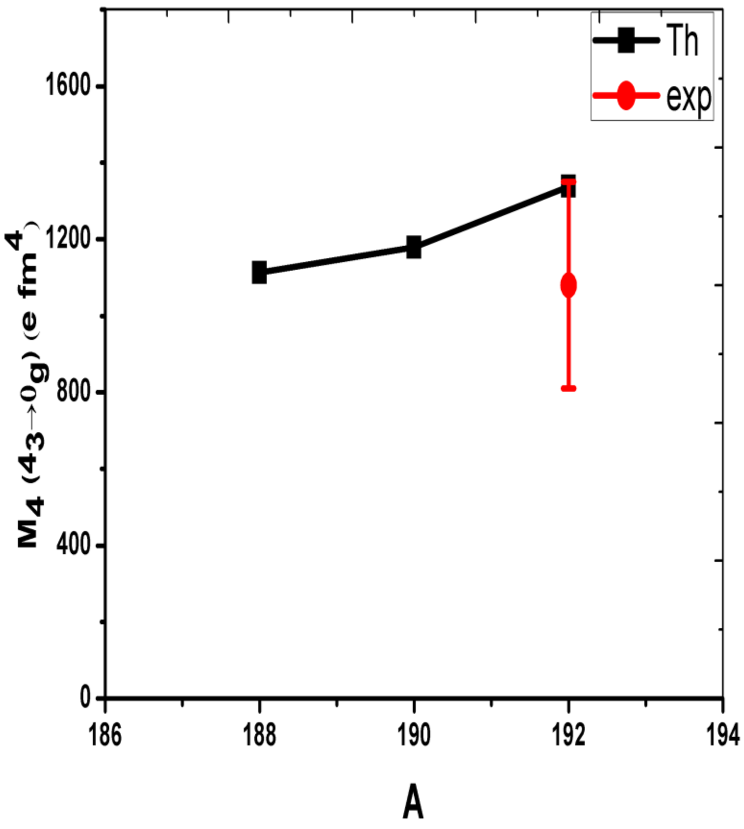


$R_4 = 2$ if $|4^+> = |\gamma\gamma>$

Ψ(QPM) $\sim 0.60\, |n=1,4^+> + 0.35\, |\gamma\gamma>$

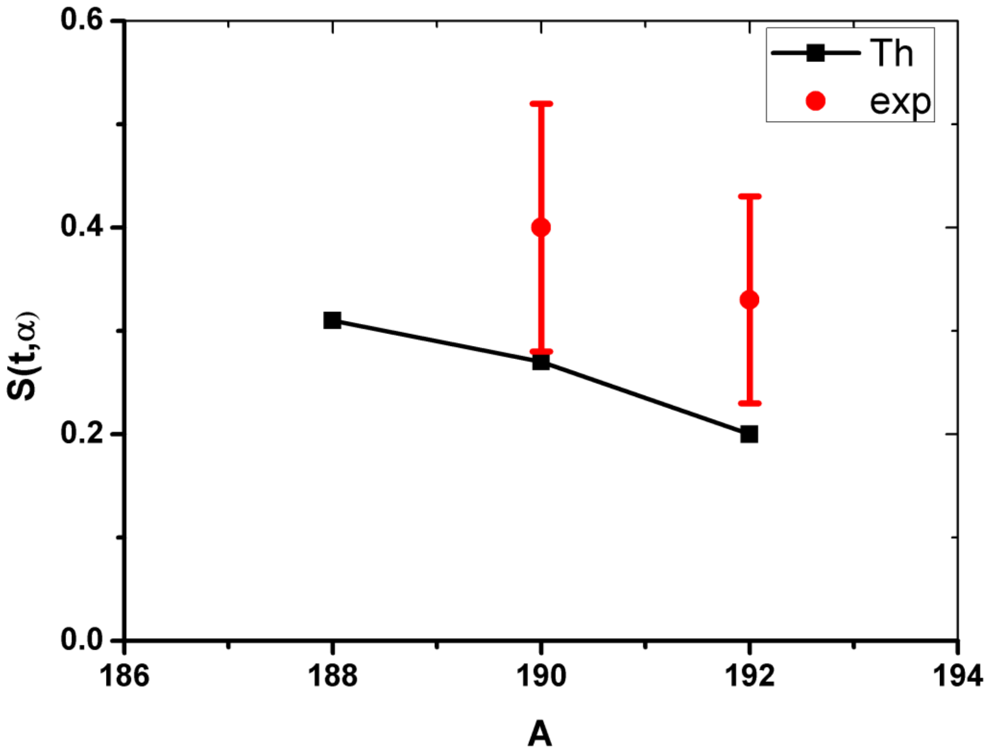
$$\mathcal{M}_4\,(4^+ \rightarrow 0^+_g) = \langle 4^+ \| M(\lambda=4) \| 0^+_g \rangle$$





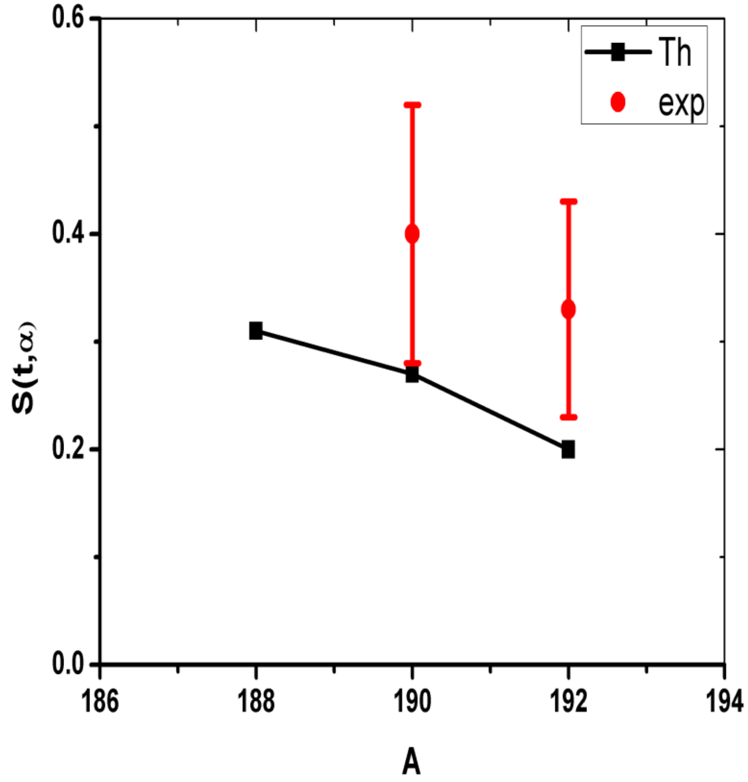
$\Psi(\mathrm{QPM}) \sim 0.60\,|n=1,4^+\rangle + 0.35\,|\gamma\gamma\rangle$

(t,α) reaction: Spectroscopic factor



$\Psi(QPM) \sim 0.60\,|n=1,4^{+}\rangle + 0.35\,|\gamma\gamma\rangle$

(t,α) and (^{3}He,d) reaction: Spectroscopic factor



Dominant configuration

$5/2^+[402]_\pi + 3/2^+ [402]_\pi$

^{188}Os: 32%

^{190}Os: 30%

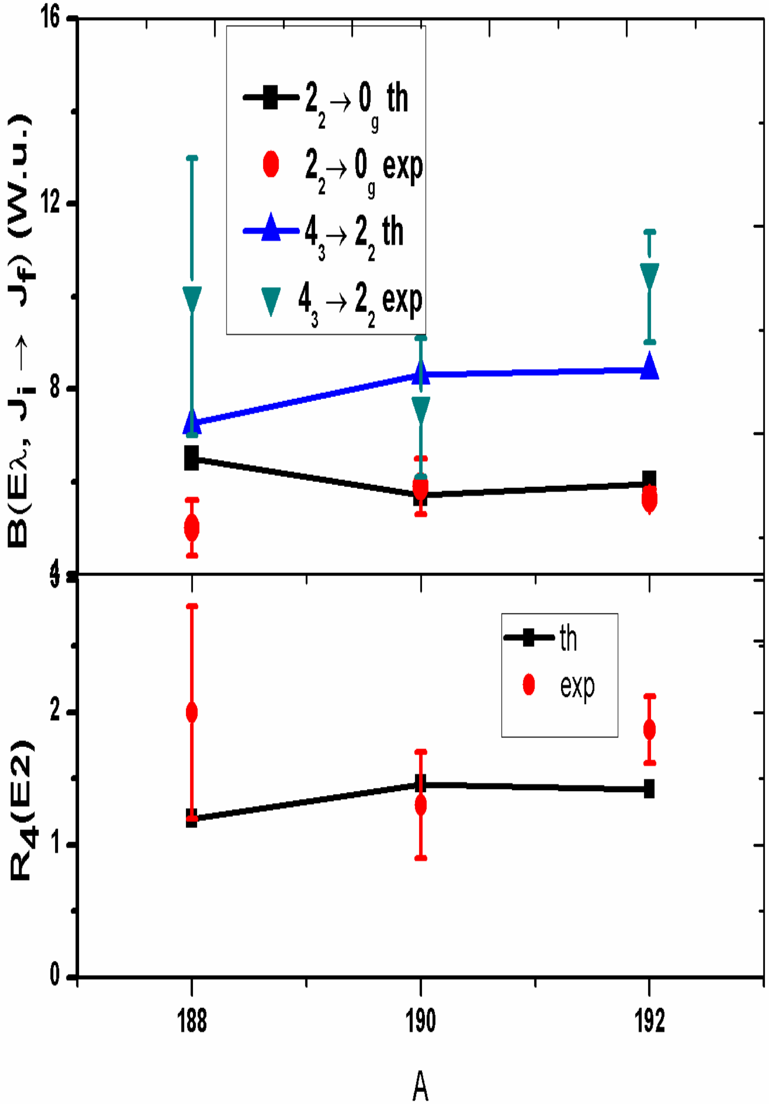
^{192}Os: 35%

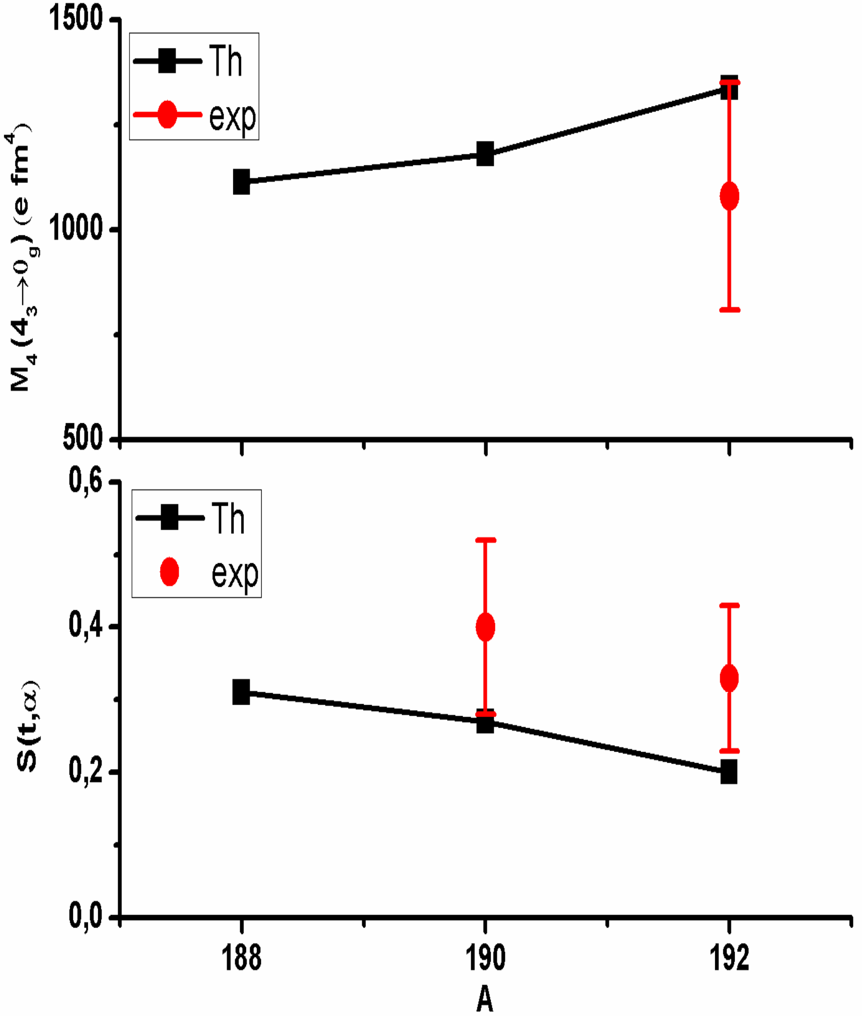
In agreement with recent experiments

(P. Garrett et al. Finustar 2 (08) and private communication)

Ψ(QPM) ~ 0.60 |n=1,4$^+$> + 0.35 |γγ>

4^+: QPM versus EXP





THANK YOU