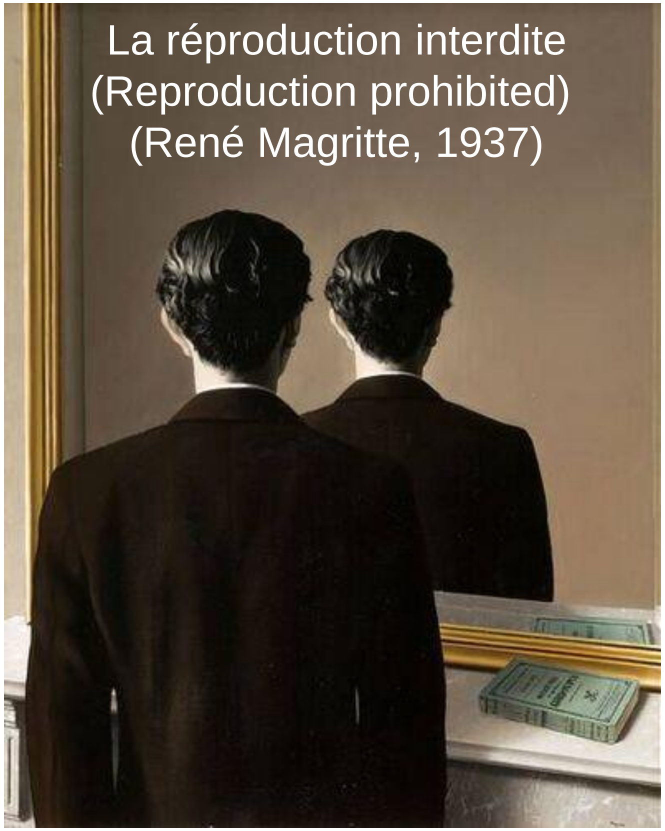

Coexisting Quadrupole Shapes in Heavy Exotic Nuclei

Piet Van Duppen
Department of Physics and Astronomy
KU Leuven, Belgium

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- Shape coexistence in heavy nuclei: initial indications
- Coulex and laser spectroscopy studies in the neutron-deficient nuclei around Z=82 (lead region): experiment versus theory
- New approaches towards the heaviest nuclei:
    - In-gas laser ionization spectroscopy
- Conclusion and ~~outlook~~ reflections

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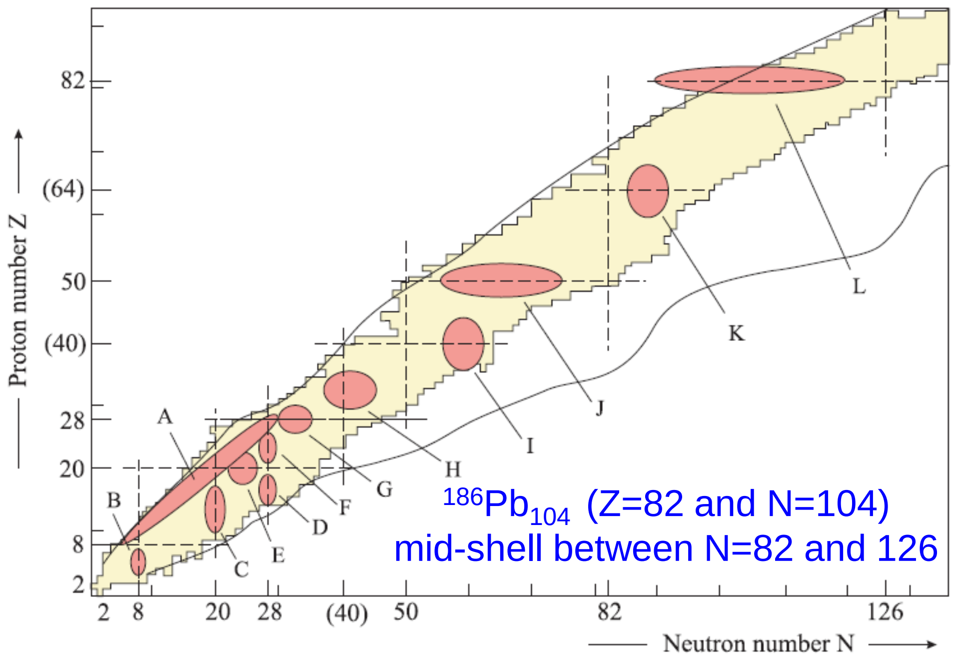
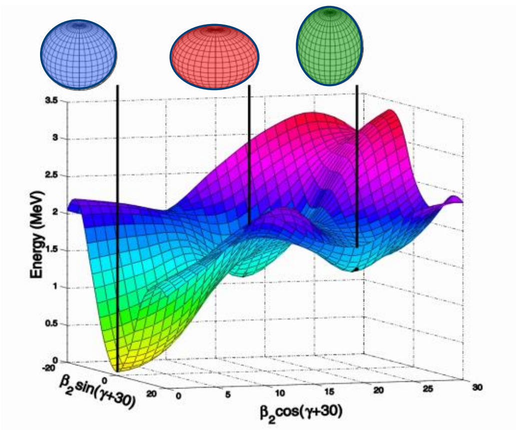
• Shape Coexistence in Atomic Nuclei

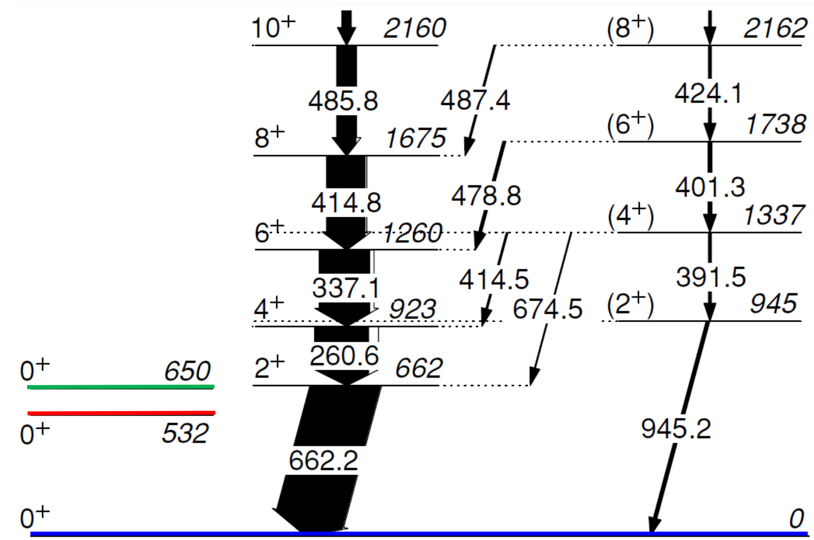
- states with different (*quadrupole*) shapes at similar binding energy
- the result of the interplay between two opposing tendencies:
    - stabilizing effect of closed shells (and subshells):
    - residual proton-neutron interaction: correlation energy

(Heyde and Wood, Review Modern Physics (2011))





Potential Energy Surface for ^{186}Pb

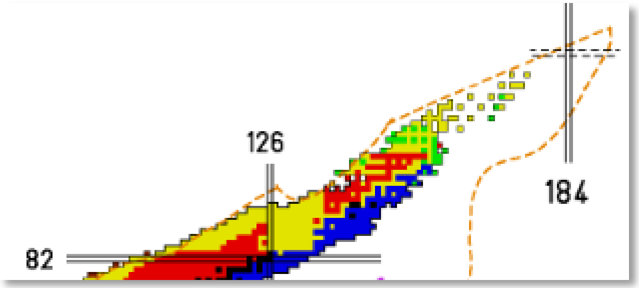


$^{186}Pb_{104}$

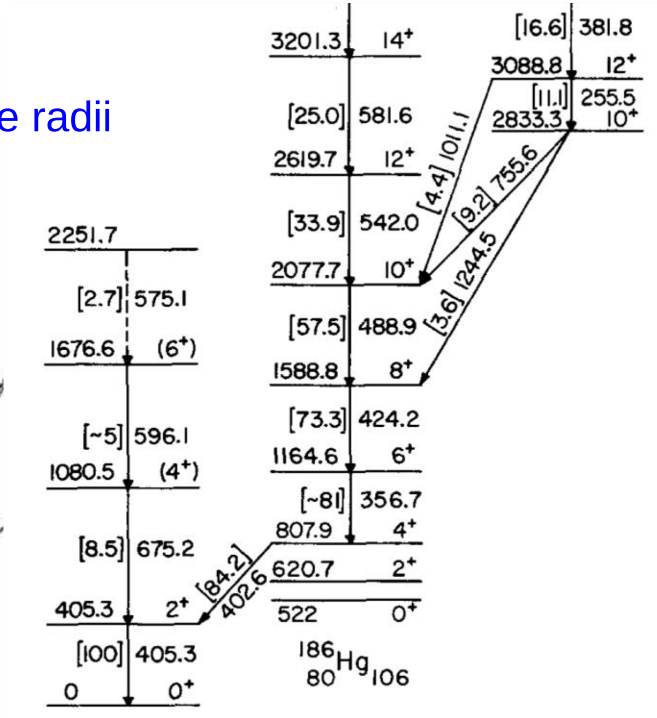
see also talks by R. Julin and J. Pakarinen

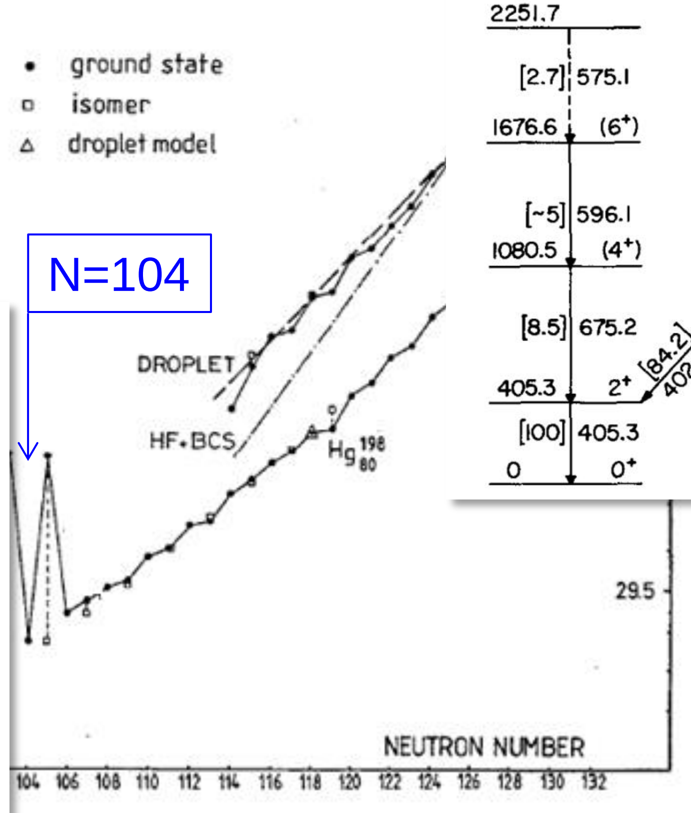
Andreyev,- Nature 405 (2000), Pakarinen,- PRC75 (2007)

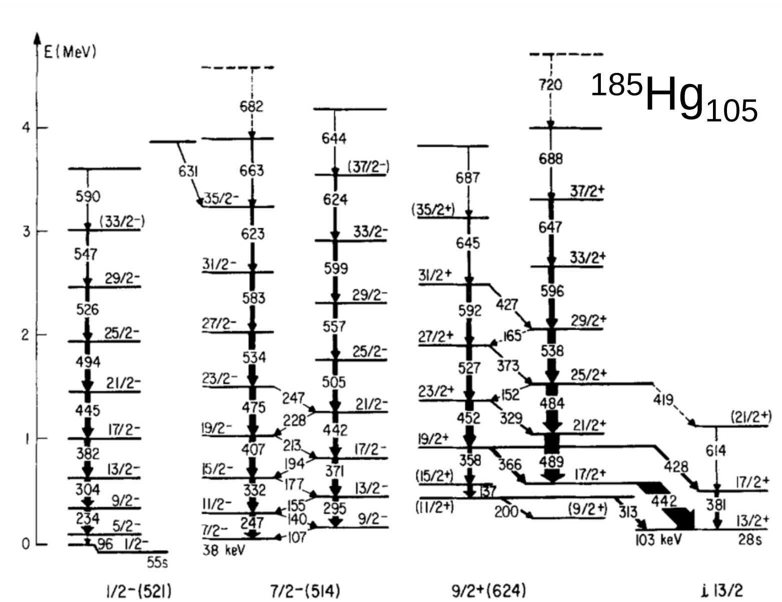
- Shape coexistence in heavy nuclei: initial indications



isotope shifts → charge radii

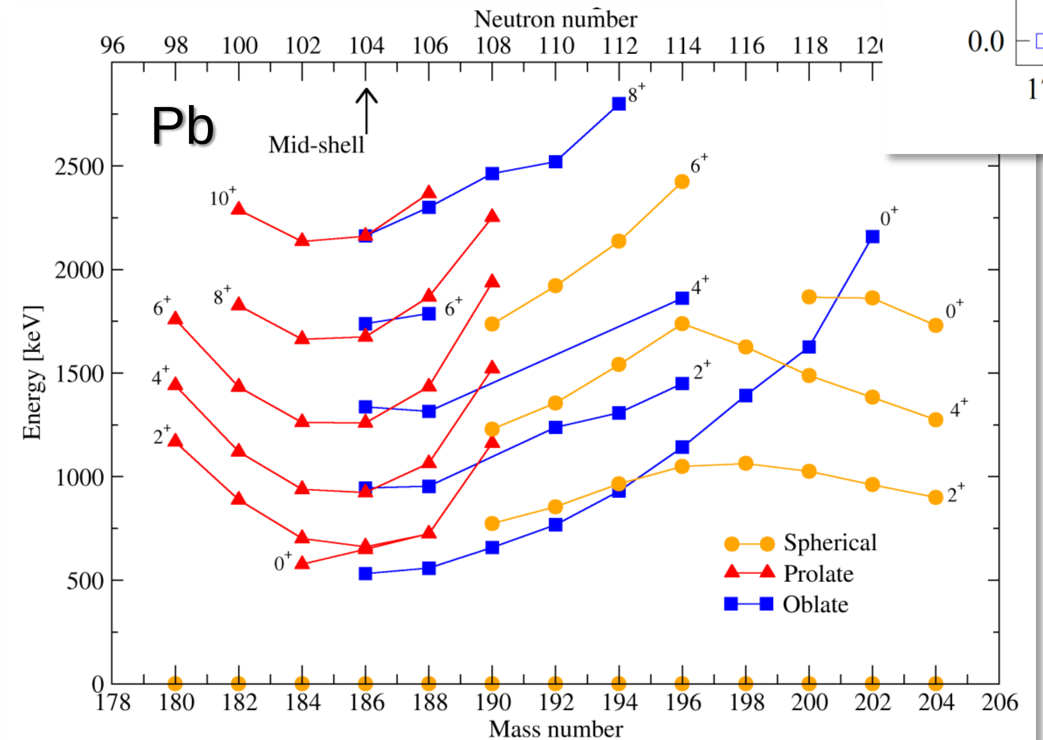


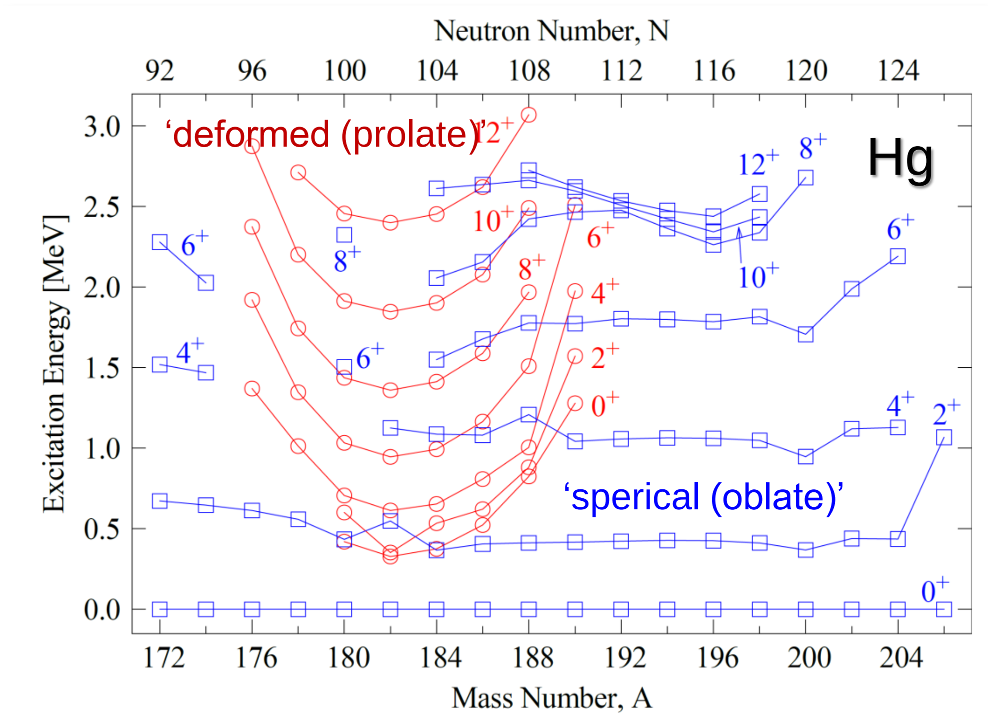


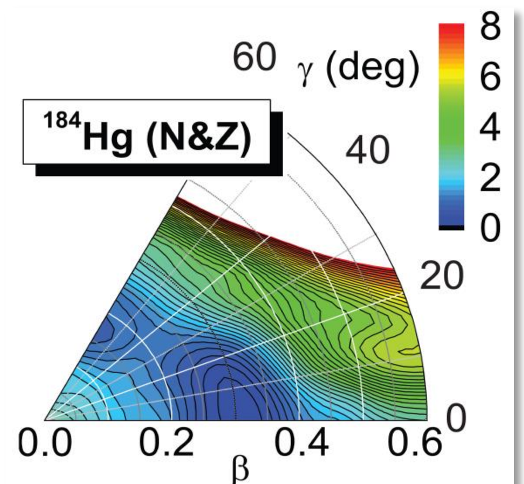


Bonn,- PLB 38 (1972), Hannachi,- ZP A370 (1988), Ma,- PLB167 (1986)
Janssens,- PLB131 (1983), Cole,- PRL37 (1976)

- Level energy systematics





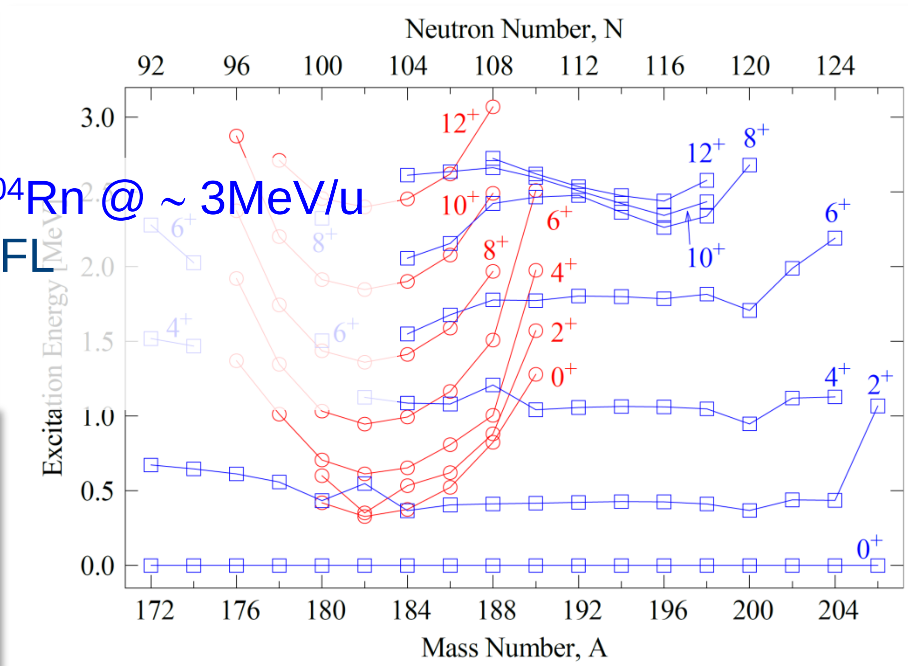


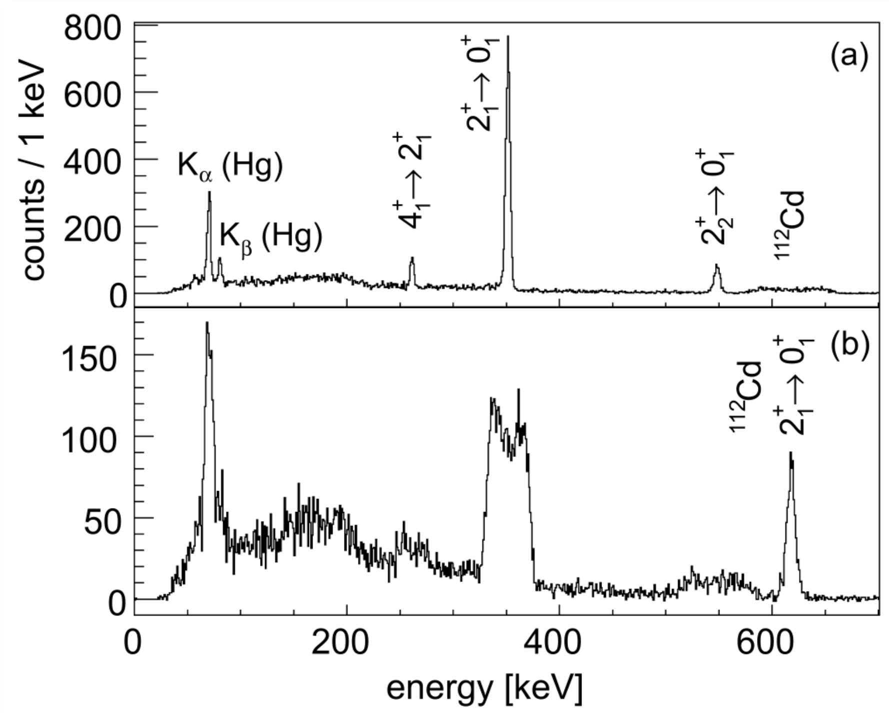
Yao PRC87 (2013)
Egido PRL93 (2004)

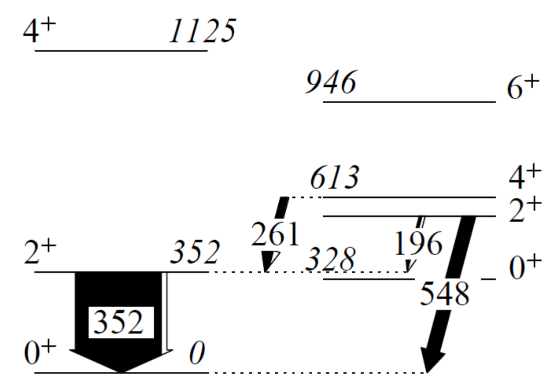
Dracoulis PRC 69 (2004), Grahn PRL 97 (2006), Kondev PRC 62 (2000), Sandzelius PRC79 (2009), Elseviers PRC84 (2011)

- Coulex of $^{182-188}$Hg, $^{188-198}$Pb, $^{196-202}$Po, $^{202-204}$Rn @ ~ 3MeV/u
- Life time measurements: $^{184-188}$Hg: ANL, JYFL
- β-decay studies: ^{182,184}Tl – ^{182,184}Hg

γ-branchings, conversion coefficients







^{182}Hg ($T_{1/2}$=10.8 s; 3500 pps)

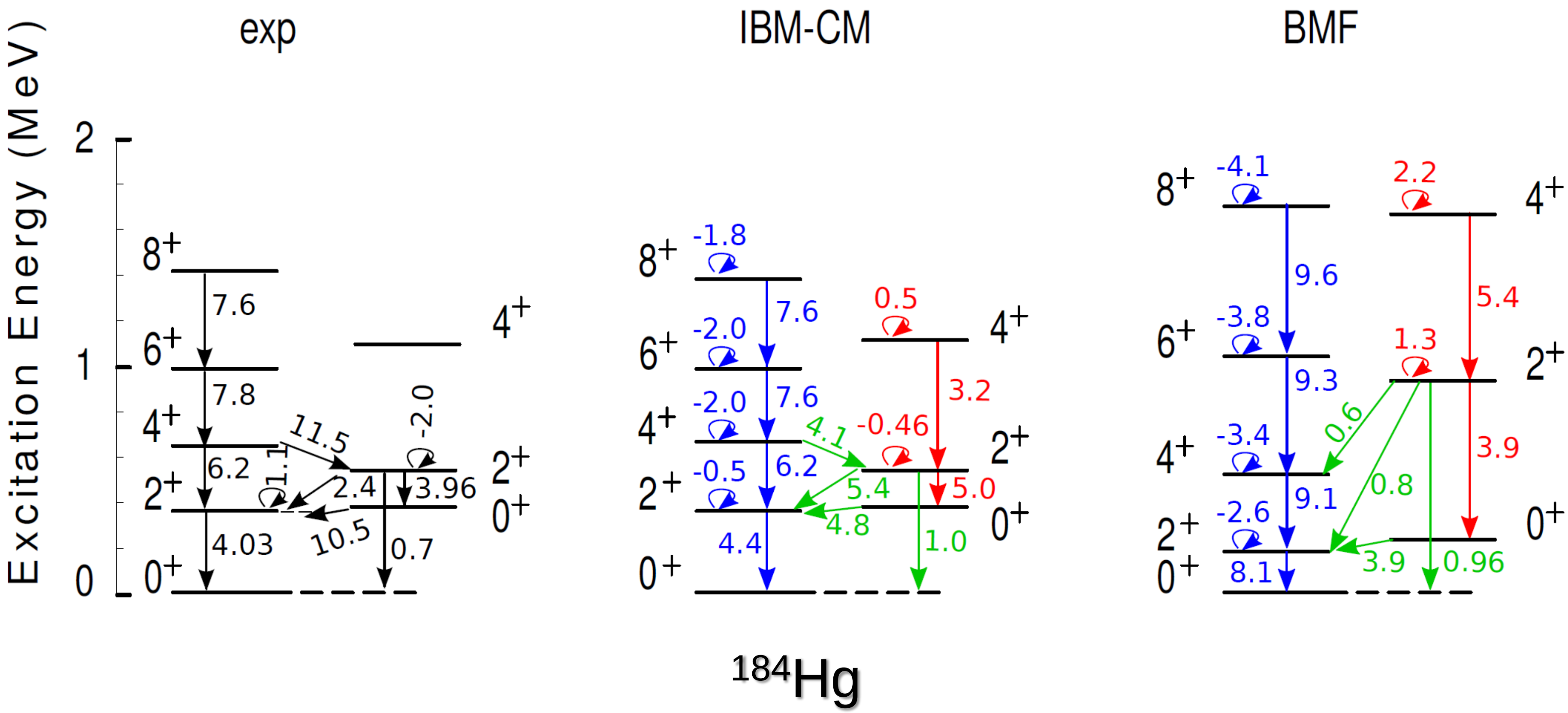
$\langle I_i \| E2 \| I_f \rangle$ (eb)	^{182}Hg	^{184}Hg	^{186}Hg	^{188}Hg
$\langle 0_1^+ \| E2 \| 2_1^+ \rangle$	$1.29^{+0.04}_{-0.03}$	1.27 (3)	$1.25^{+0.10}_{-0.07}$	1.31 (10)

Bree PRL 112 (2014), Gaffney PRC 91 (2015), Kesteloot - Pakarinen (to be publ.)

• Comparison with theory

Interacting Boson Model Configuration Mixing

Beyond Mean Field



• Transitional (arrows) and spectroscopic (loops) quadrupole moments given in eb units

• Quadrupole Sum Rules

- relate experimental ME2's with quadrupole deformation parameters

(D. Cline, Ann Rev Nucl Part Sci 36 (1986) 683)

Overall deformation ~ β ~ Q^2

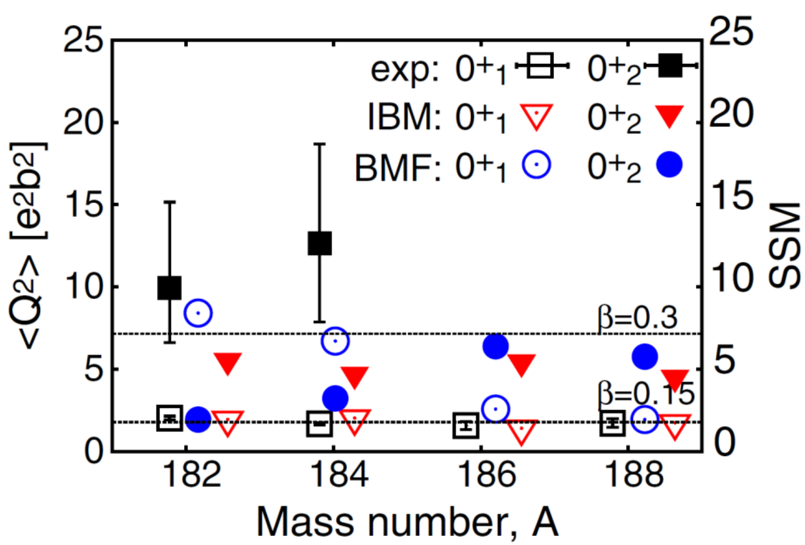
$$\frac{1}{\sqrt{5}}\langle Q^2\rangle = \langle i\,|[E2\times E2]_0|\,i\rangle =$$

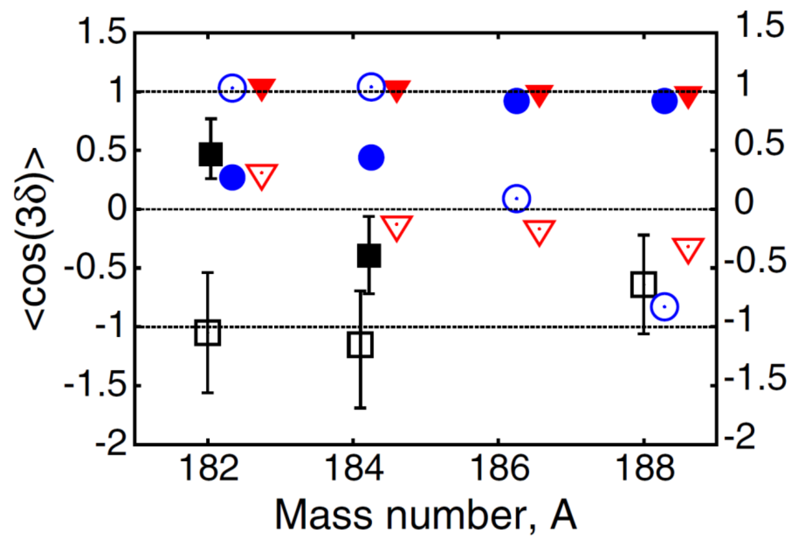
$$= \frac{1}{\sqrt{(2I_i+1)}}\sum_t \langle i\|E2\|t\rangle\langle t\|E2\|i\rangle \left\{ \begin{array}{ccc} 2 & 2 & 0 \\ I_i & I_i & I_t \end{array} \right\}$$

Triaxiality ~ γ ~ <cos3δ> :

$$\sqrt{\frac{2}{35}}\langle Q^3 cos3\delta\rangle = \langle i\,|[[E2\times E2]_2\times E2]_0|\,i\rangle =$$

$$= \frac{\mp 1}{(2I_i+1)}\sum_{t,u} \langle i\|E2\|u\rangle\langle u\|E2\|t\rangle\langle t\|E2\|i\rangle \left\{ \begin{array}{ccc} 2 & 2 & 2 \\ I_i & I_t & I_u \end{array} \right\}$$





→ need more precise experimental matrix elements (e.g. HIE ISOLDE - 5 MeV/u)

→ need theoretical developments (including tri-axiallity, odd-mass nuclei): microscopic origin of shape coexistence

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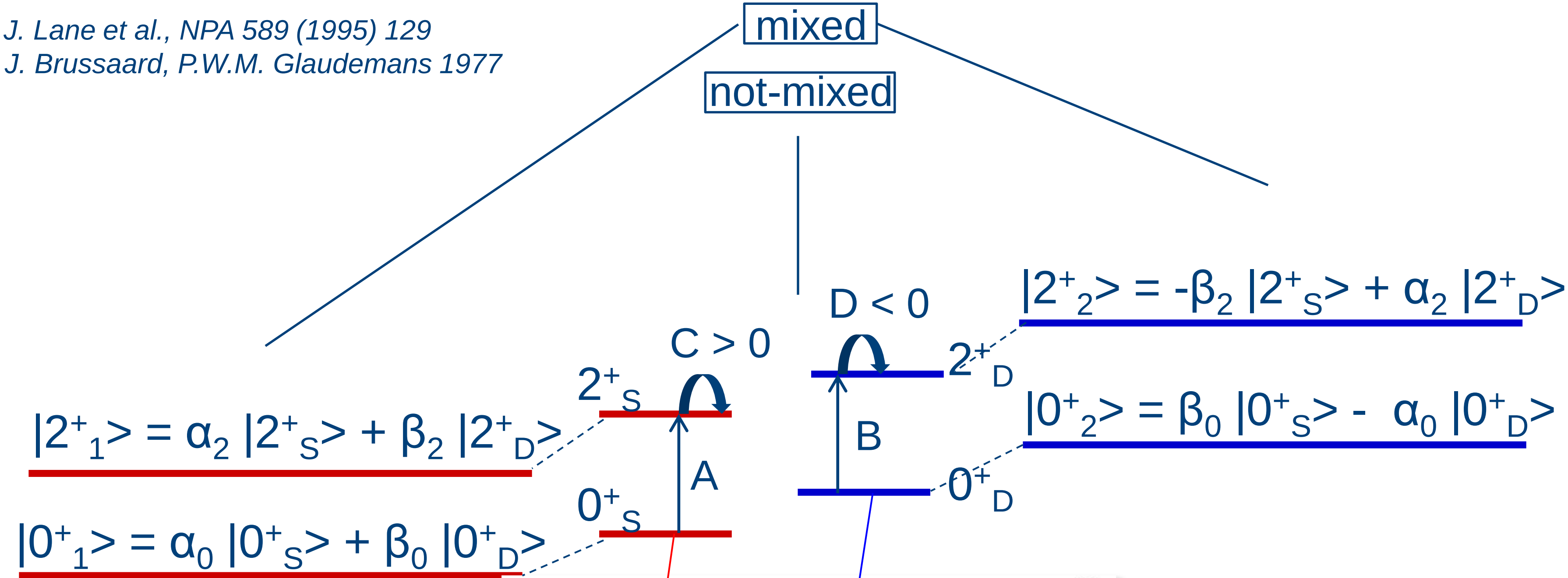
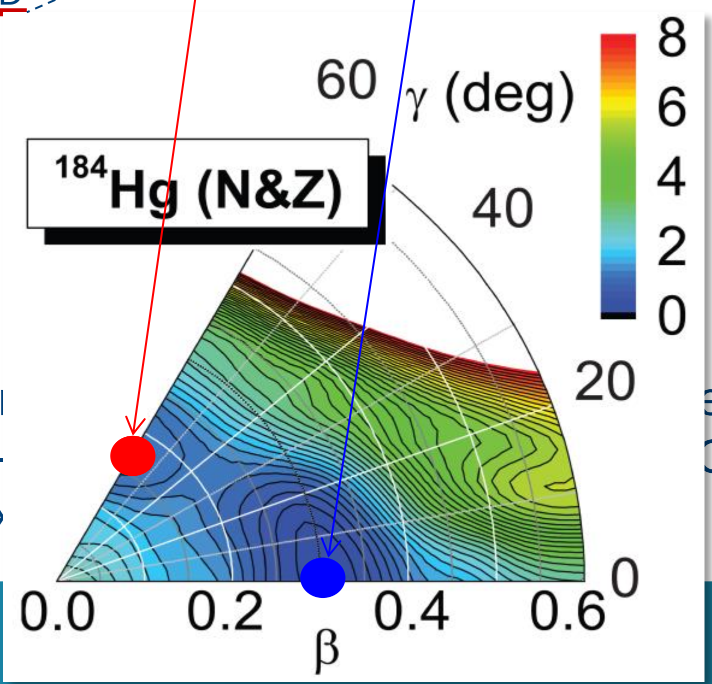
- Two level mixing calculations

G.J. Lane et al., NPA 589 (1995) 129
P. J. Brussaard, P.W.M. Glaudemans 1977





Experime ... expressed by:

- un- ... C, D)
- mi

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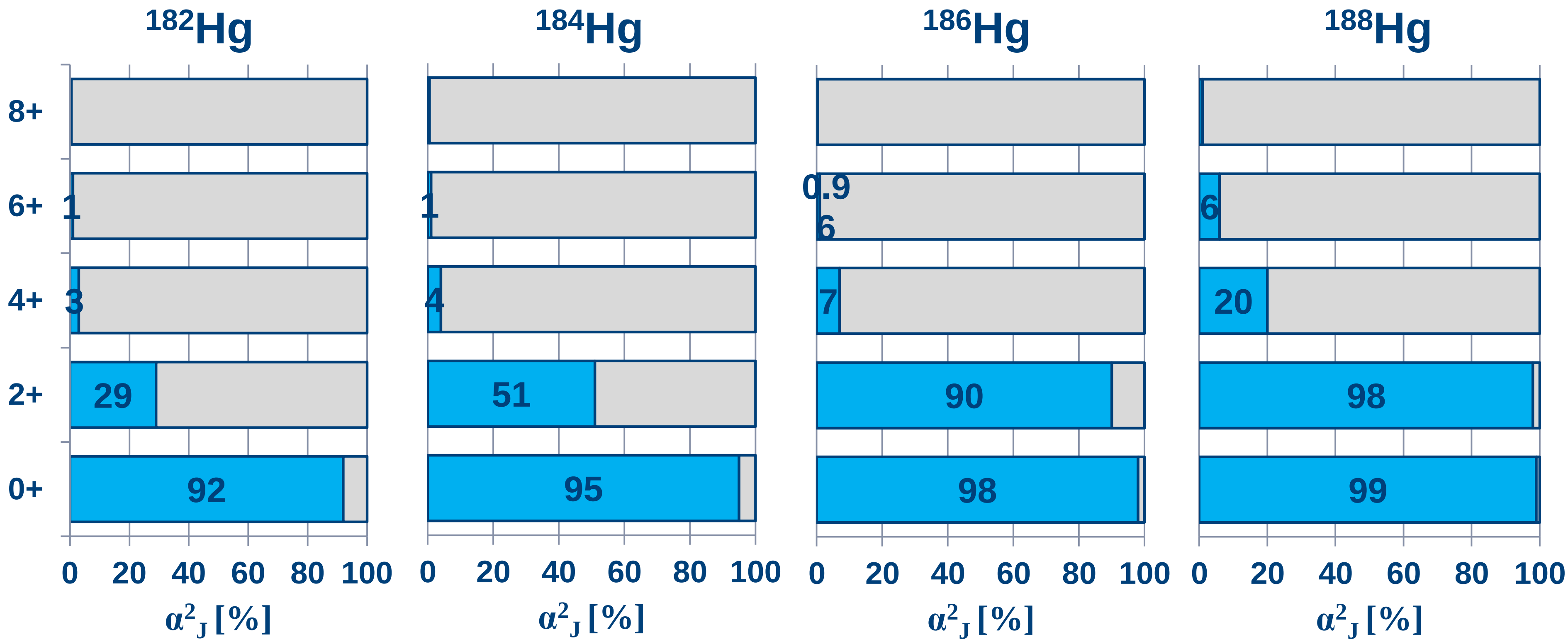
- Two level mixing calculations

Deduced from fitting the higher-lying levels using the variable moment of inertia model

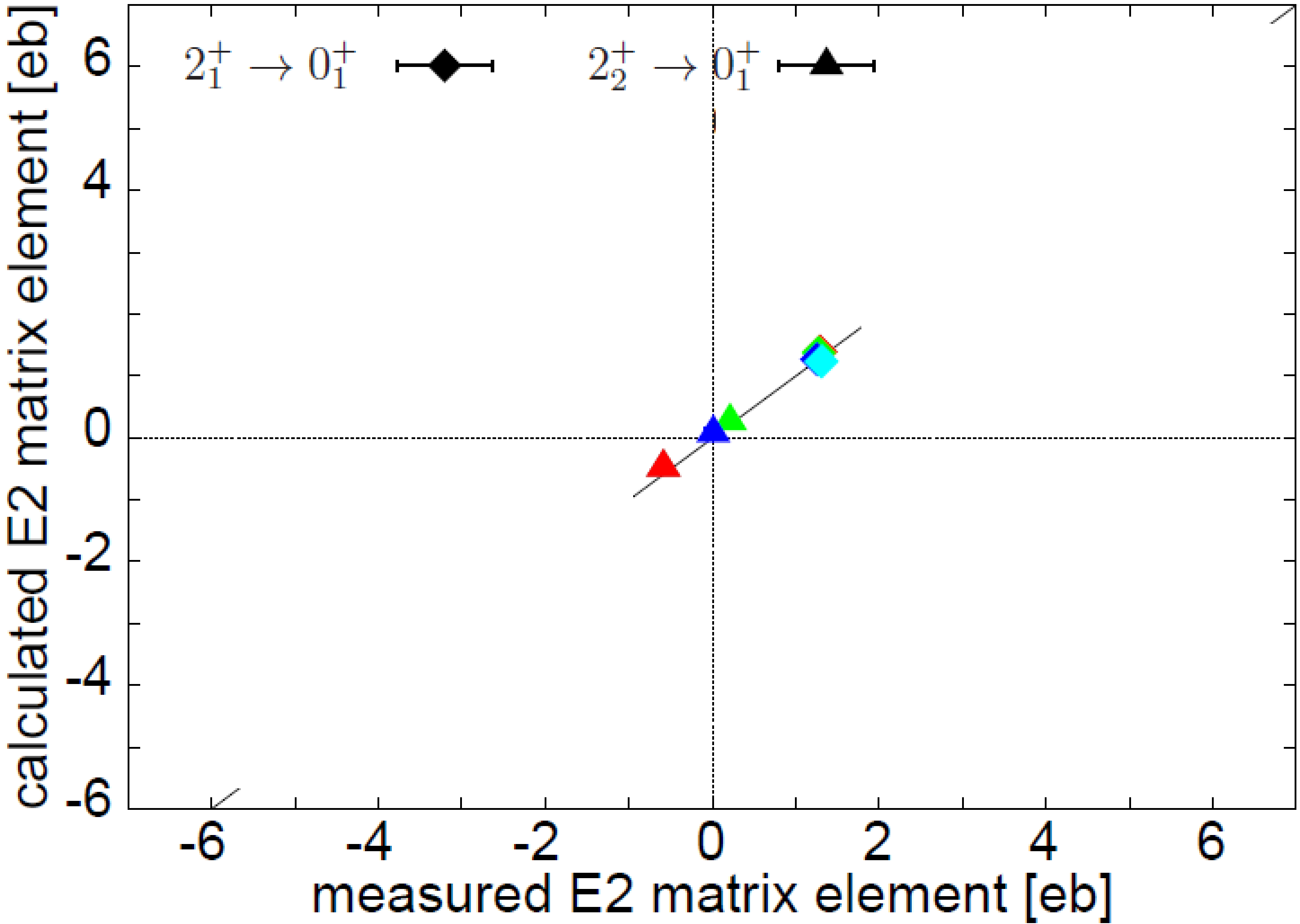


- 0^+ states: only weakly mixed for all $^{182-188}$Hg
- 2^+ states: mixing is changing from 29% up to 98%
- 4^+ states: dominant deformed configuration for all $^{182-188}$Hg

- Two level mixing calculations

^{182}Hg: $\alpha_2^2 = 29\%$ $\alpha_4^2 = 3\%$
^{184}Hg: $\alpha_2^2 = 51\%$ $\alpha_4^2 = 4\%$
^{186}Hg: $\alpha_2^2 = 90\%$ $\alpha_4^2 = 7\%$
^{188}Hg: $\alpha_2^2 = 98\%$ $\alpha_4^2 = 20\%$

fitted un-mixed ME2's:
A = $\langle 0^+_S || E2 || 2^+_S \rangle$ = 1.2 eb
B = $\langle 0^+_D || E2 || 2^+_D \rangle$ = 3.3 eb
C = $\langle 2^+_S || E2 || 2^+_S \rangle$ = 1.8 eb
D = $\langle 2^+_D || E2 || 2^+_D \rangle$ = -4.0 eb



- Two level mixing calculations

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fitted un-mixed ME2's:
A = $\langle 0^+_S||E2|| 2^+_S \rangle$ = 1.2 eb
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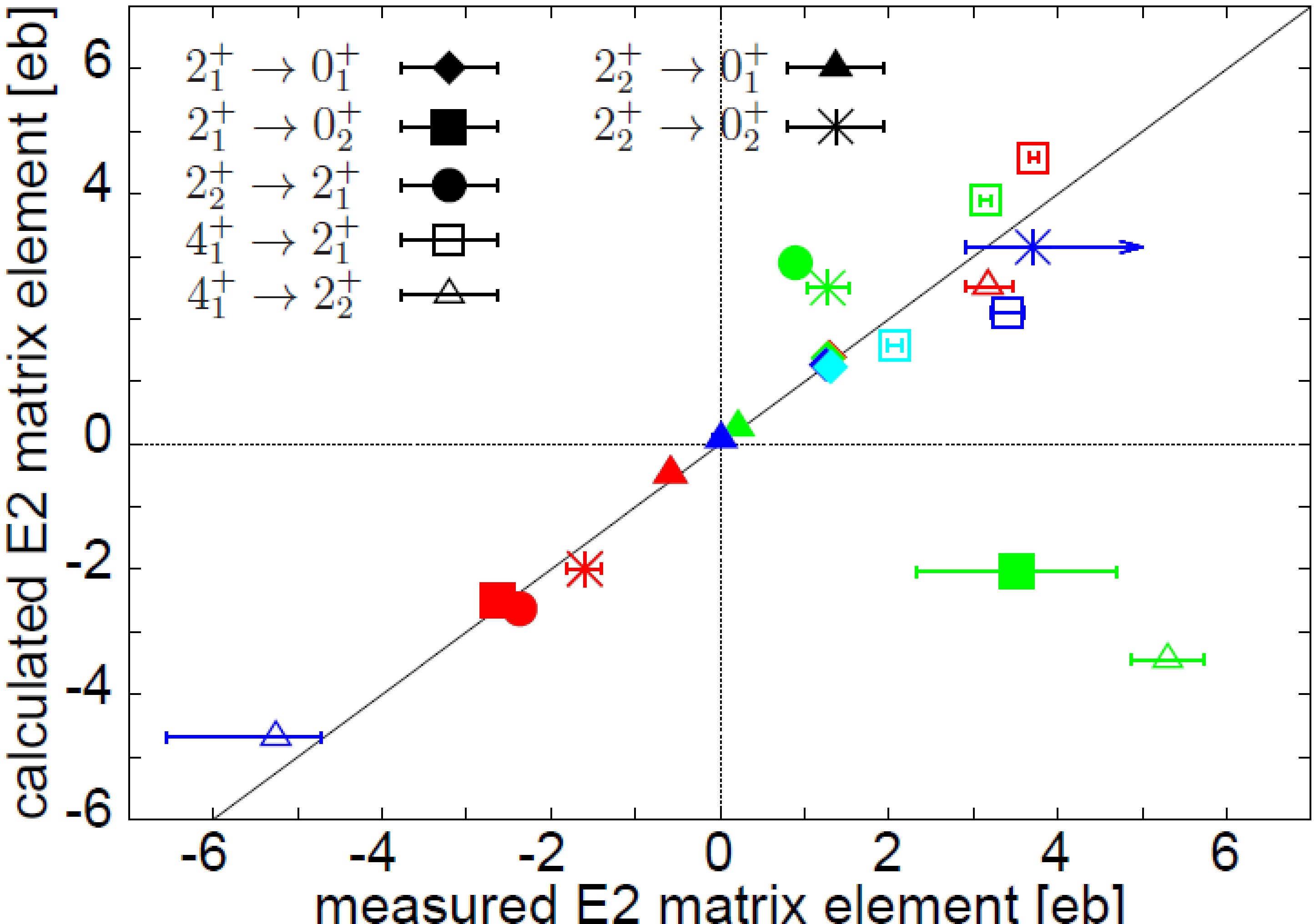
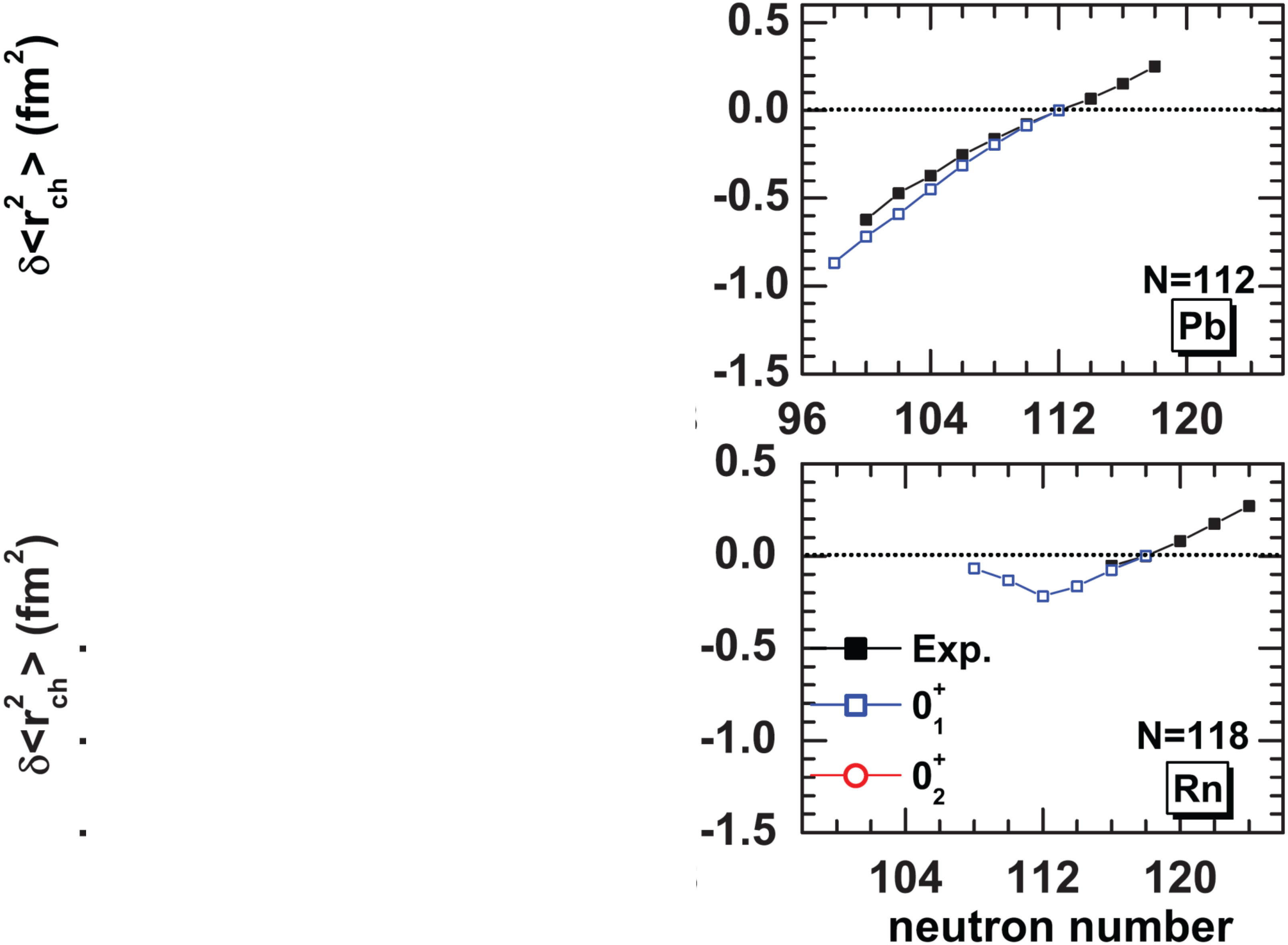
C = $\langle 2^+_S||E2|| 2^+_S \rangle$ = 1.8 eb
D = $\langle 2^+_D||E2|| 2^+_D \rangle$ = -4.0 eb



Comparison with beyond mean-field calculations

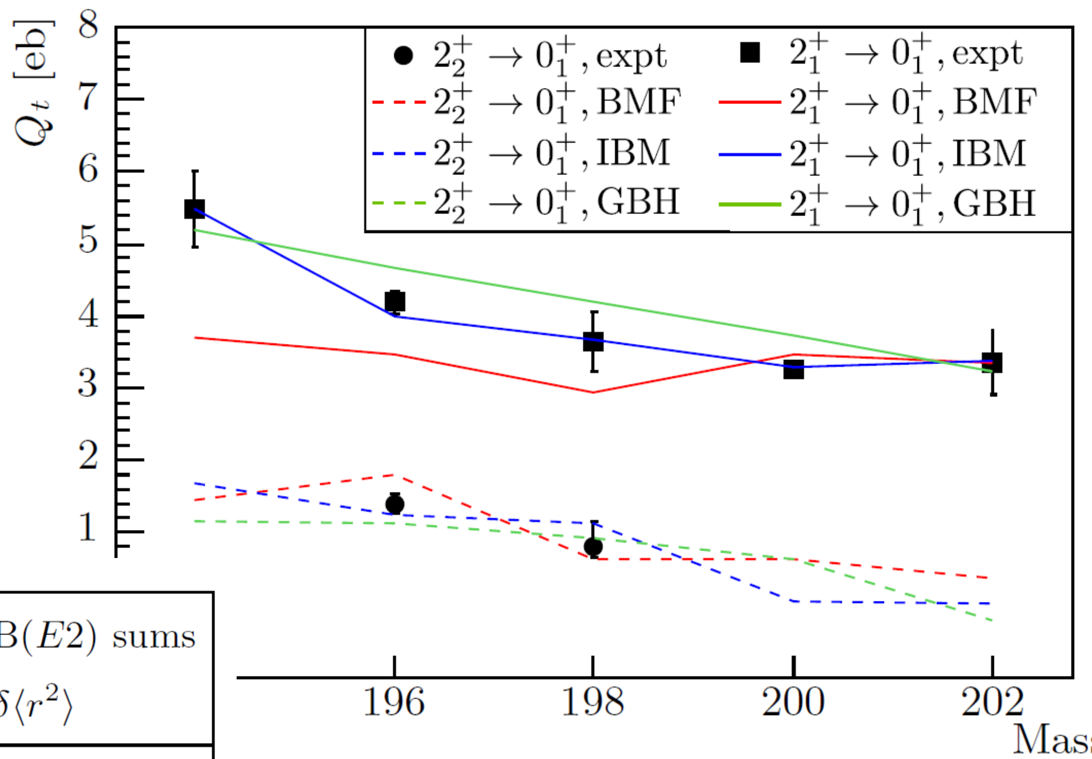


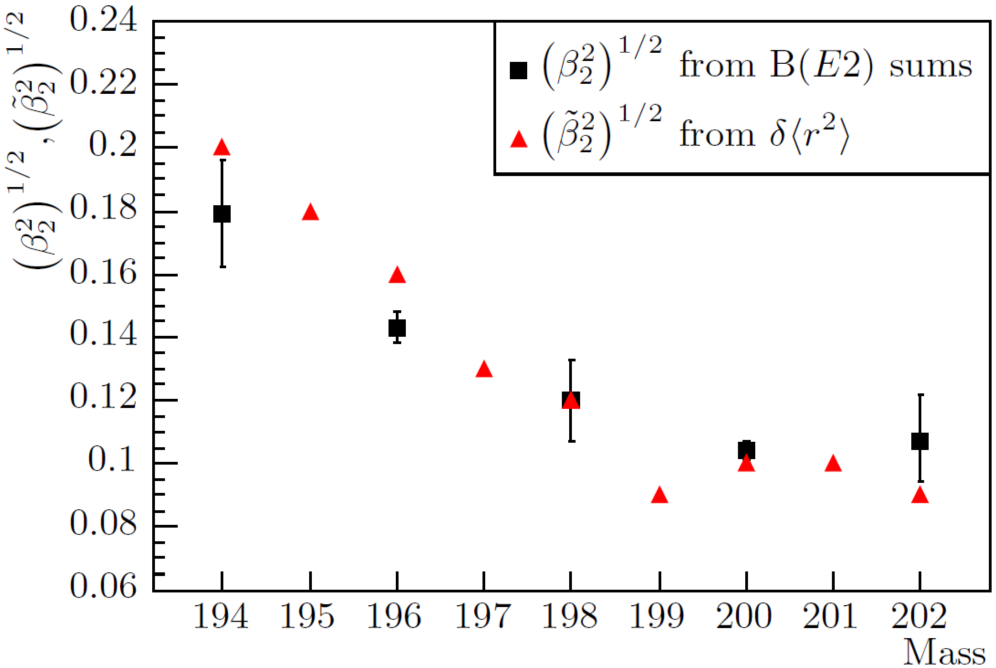
Yao PRC87 (2013)

- Polonium isotopes

$$\langle r^2 \rangle_A \approx \langle r^2 \rangle_A^{sph} \left(1 + \frac{5}{4\pi}\tilde{\beta}_2^2\right)$$

$$\sum_i |\langle 0_1^+ || E2 || 2_i^+ \rangle|^2 = \left(\frac{3}{4\pi} ZeR_0^2\right)^2 \beta_2^2$$





$$Q_t(I_i \to I_f) = \frac{\langle I_f || E2 || I_i \rangle}{\langle I_f 020 | I_i 0 \rangle} \cdot \sqrt{\frac{16\pi}{5\,(2I_f + 1)}}$$

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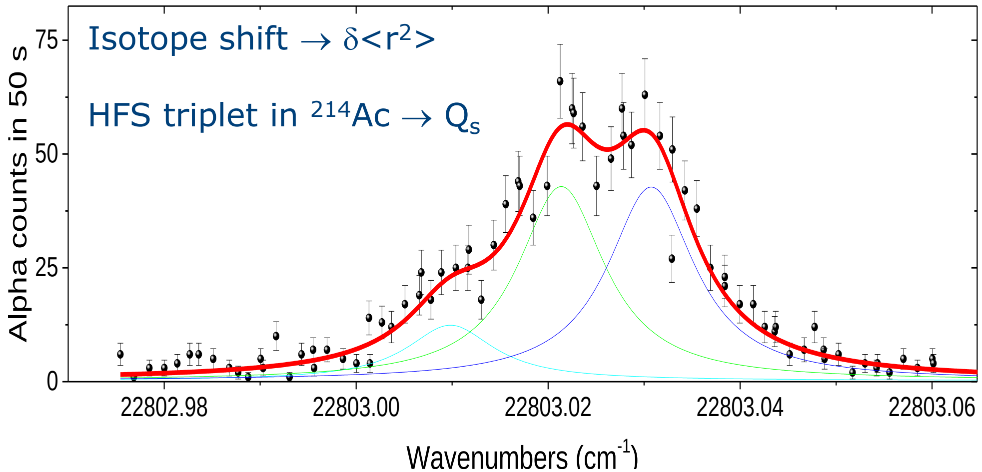
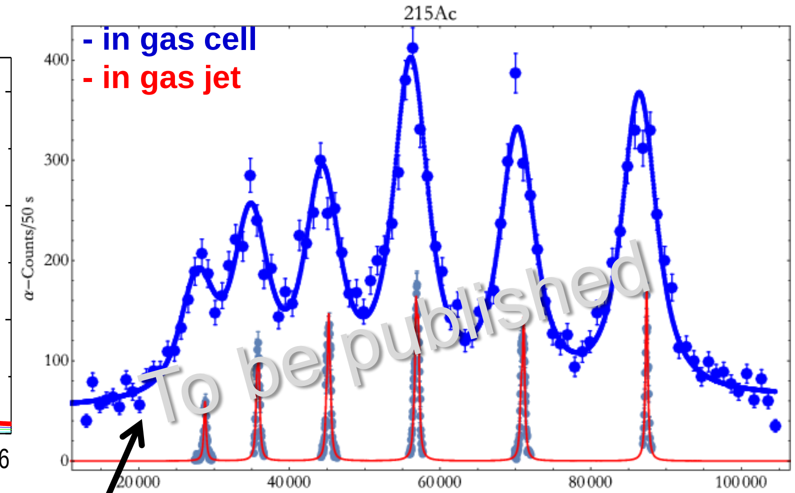
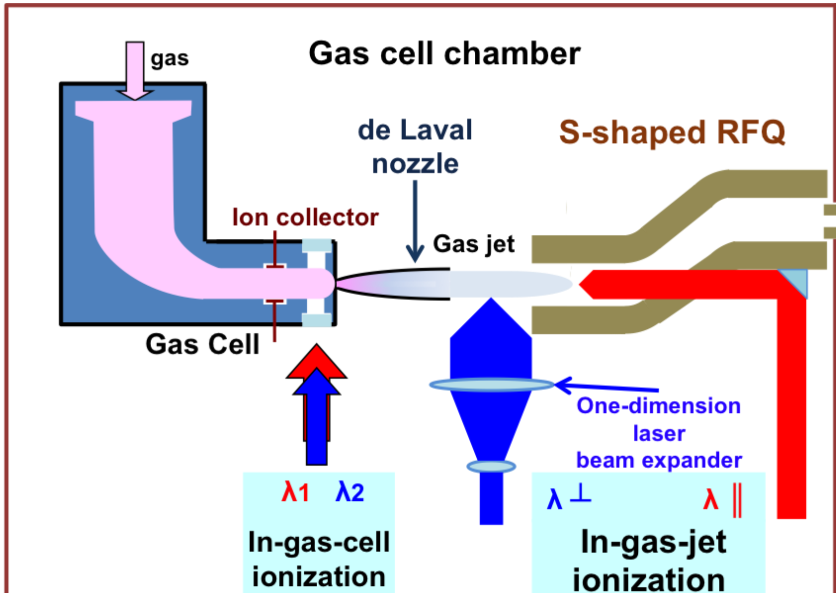
• In Gas Laser Ionization Spectroscopy (IGLIS)

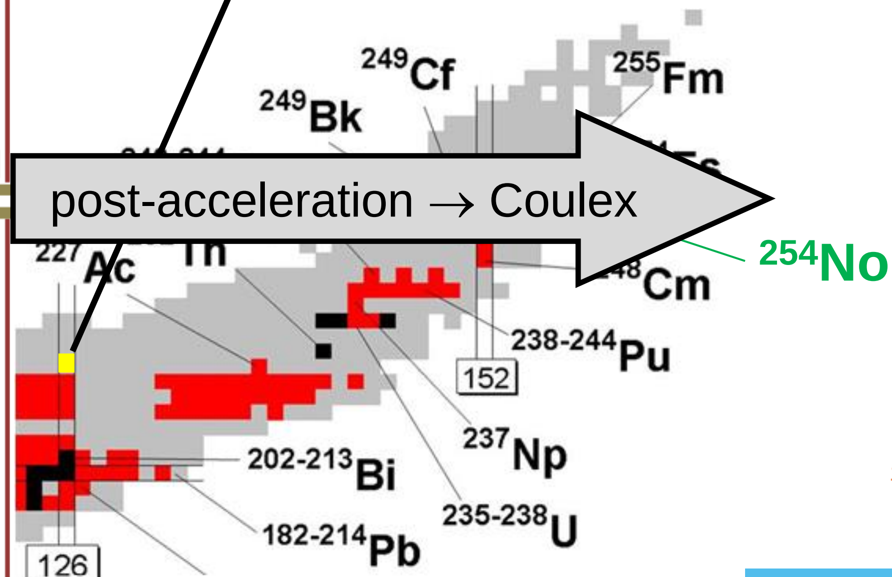
^{215}Ac $T_{1/2}$ = 0.17 s $J_\pi = (9/2^-)$







see talk M. Huyse



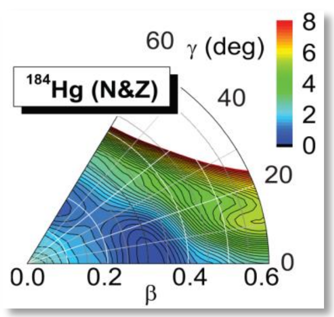
Kudryavtsev NIM B297 (2013)
Ferrer NIMB317 (2014)

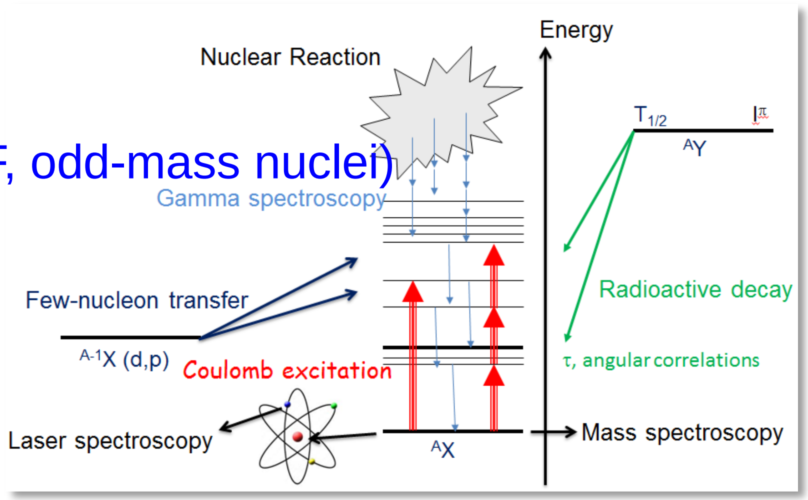
Conclusion

- Shape coexistence is firmly established (took >40 y) but the underlying microscopic mechanisms needs further experimental and theoretical input

- Need for more precise experimental data (e.g E2 matrix elements), nucleon transfer reactions and need to combine all information available (→ consistent picture)

- Further theoretical developments (triaxial DOF, odd-mass nuclei)





- New opportunities with the new facilities (see talks M. Huyse and Y. Blumenfeld)
  - actinide region: laser spectroscopy and possibly post-accelerated beams

Reflections

La plage des savants, Cargèse (1991)

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