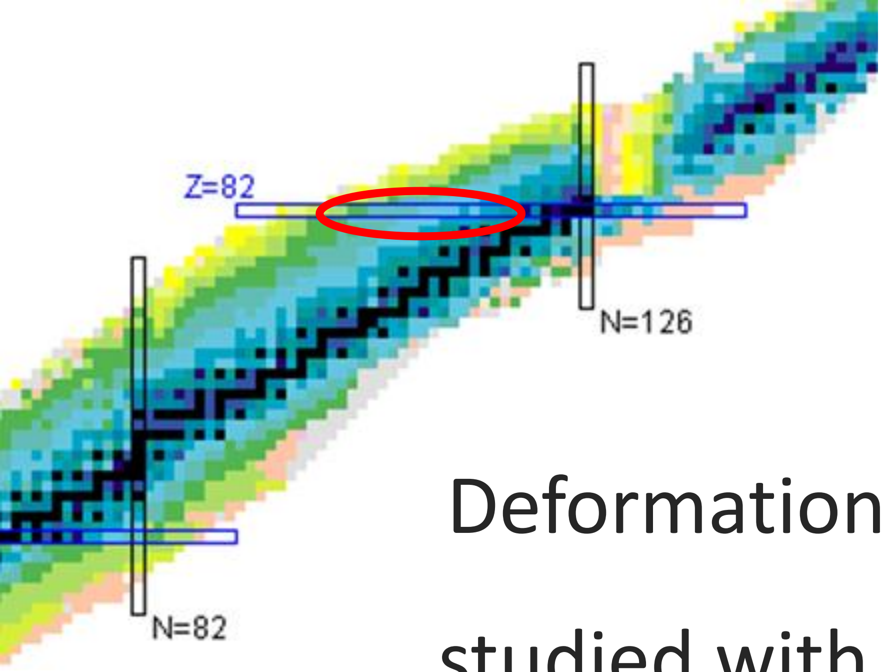


Deformation and shape coexistence studied with the Coulomb excitation in neutron-deficient Po and Hg isotopes

K. Wrzosek-Lipska

for the IS452 and IS479 collaboration

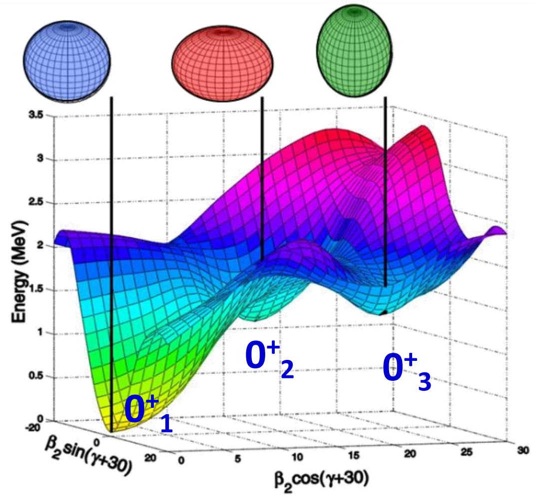
SSNET 2018 Conference, Gif-sur-Yvette, 5-9 Nov. 2018

Shape coexistence in atomic nuclei

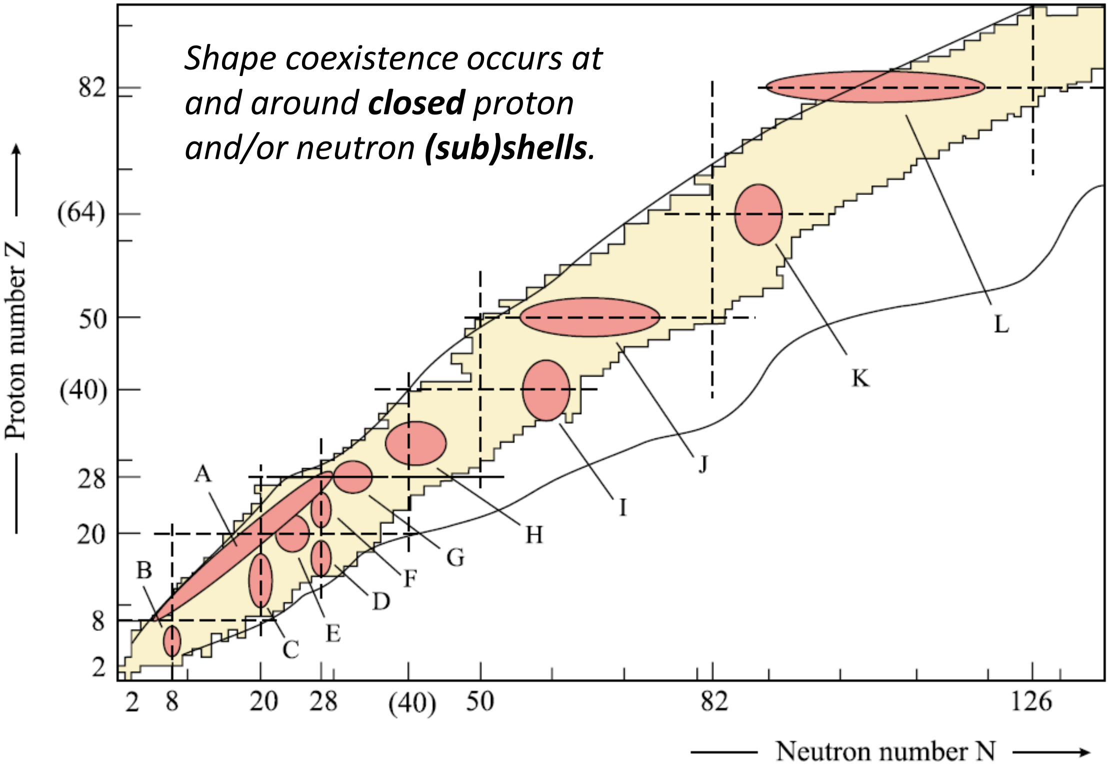
$^{186}\mathrm{Pb}_{104}$

- Presence at low energy near-degenerate states in atomic nucleus characterized by different shape.

- Interplay between two opposing tendencies:
  - ➢ Stabilizing effect of closed shells (subshells)
    → causes the nuclei to retain a spherical shape.
  - ➢ Residual proton-neutron interactions → deformation.



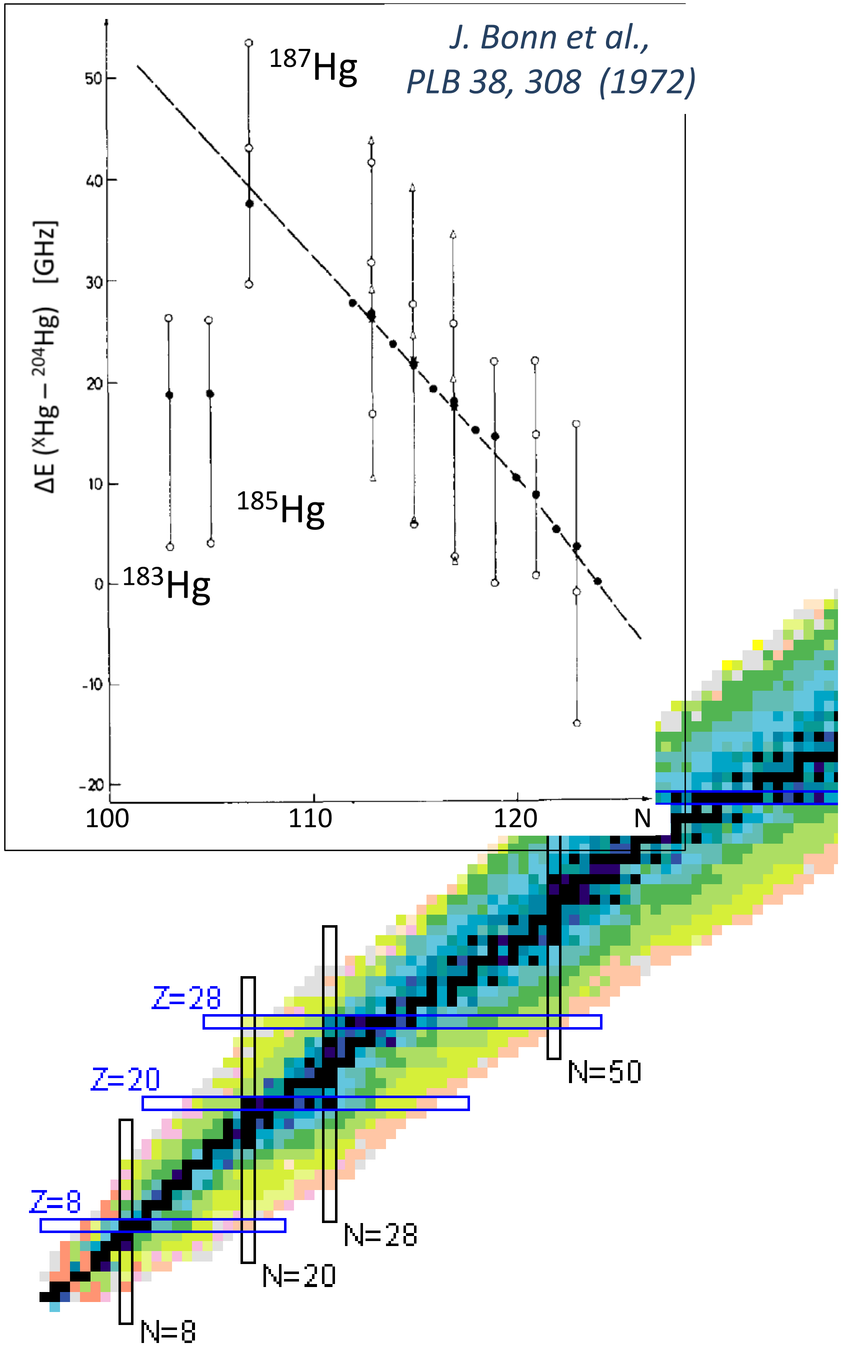
A. Andreyev et al., Nature 405:430 (2000)



*Shape coexistence occurs at and around **closed** proton and/or neutron **(sub)shells**.*

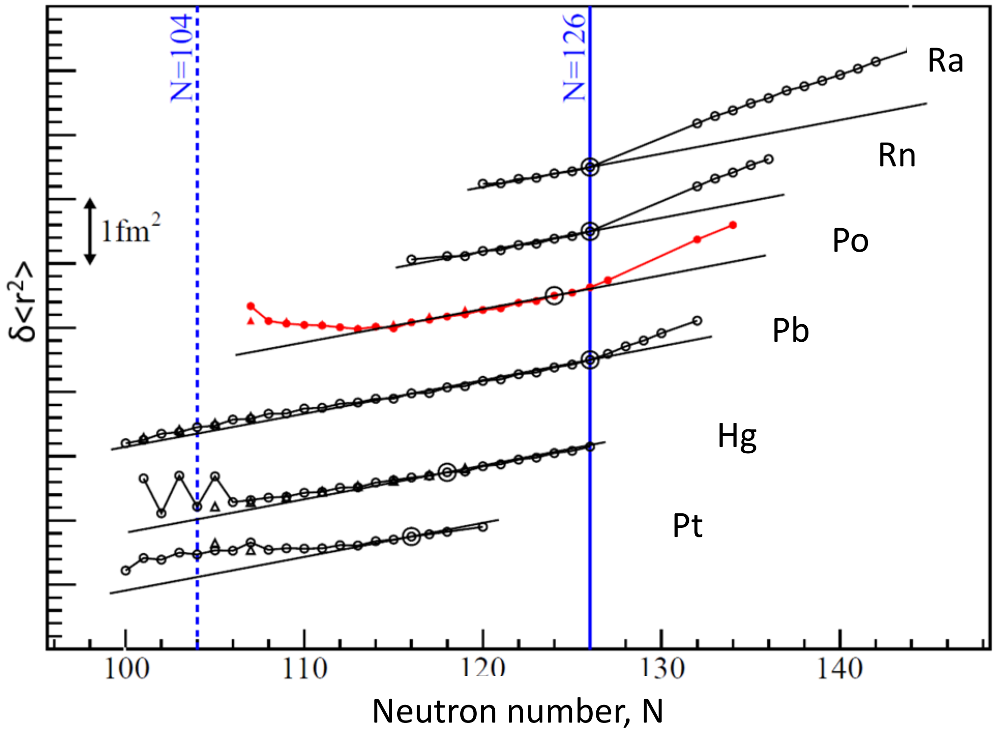
K. Heyde and J. L. Wood, Review of Modern Physics 83 (2011)

Shape coexistence around N=104 mid-shell

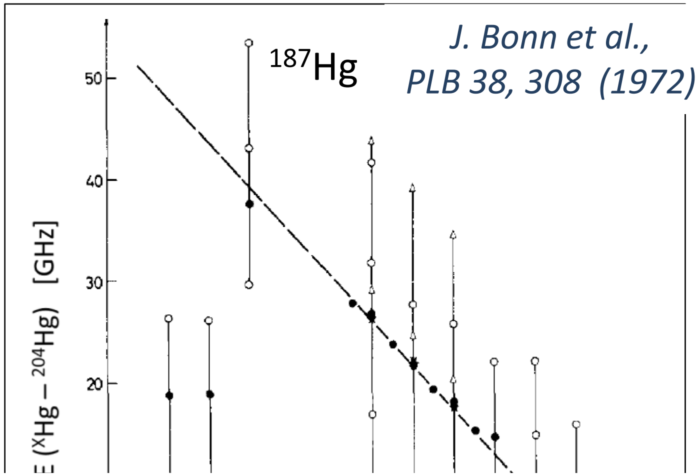

J. Bonn et al., PLB 38, 308 (1972)

T.E. Cocolios et al. PRL 106 (2011) 052503,

G. Ulm et al., Z.Phys. A325, 247 (1986)



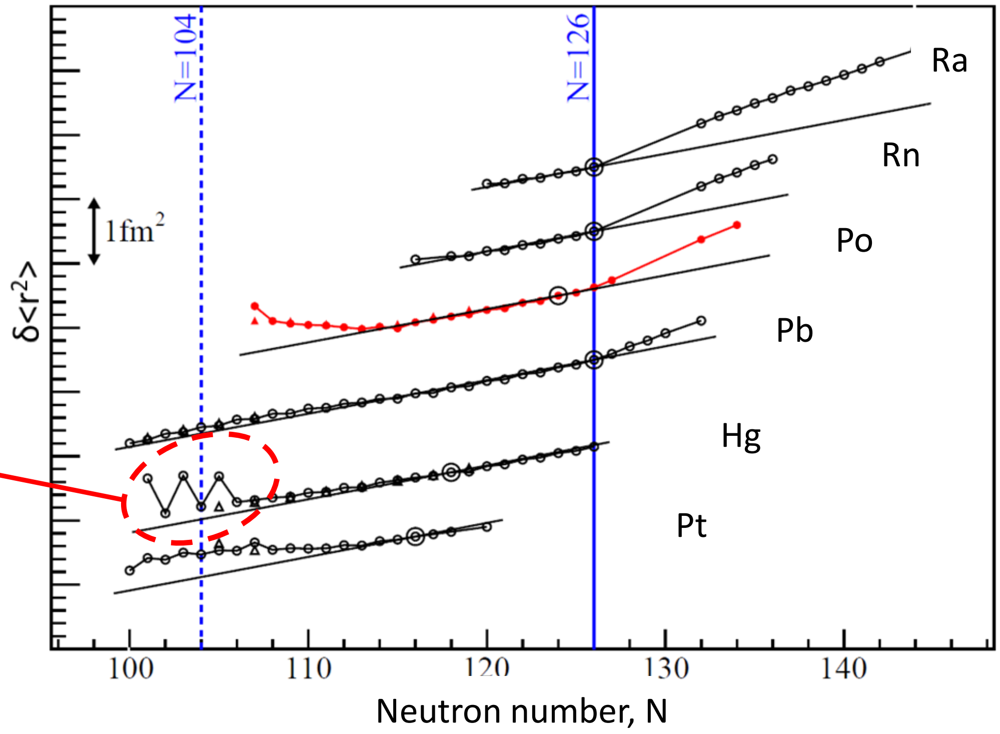
Shape coexistence around N=104 mid-shell

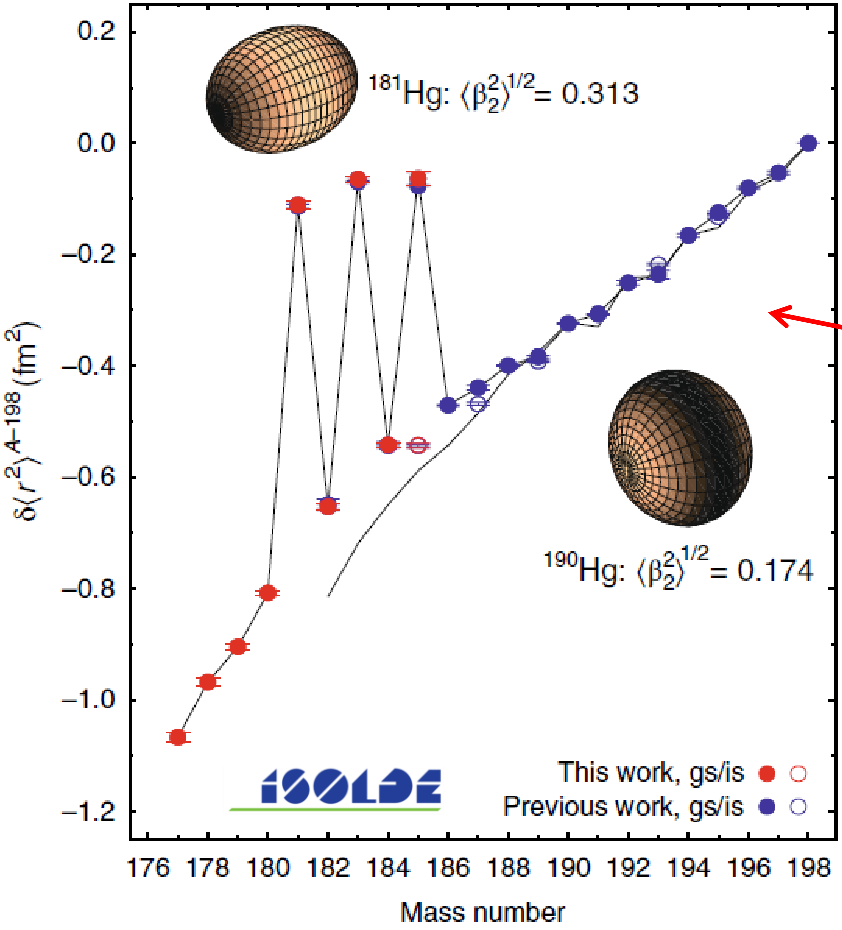


J. Bonn et al., PLB 38, 308 (1972)

T.E. Cocolios et al. PRL 106 (2011) 052503,

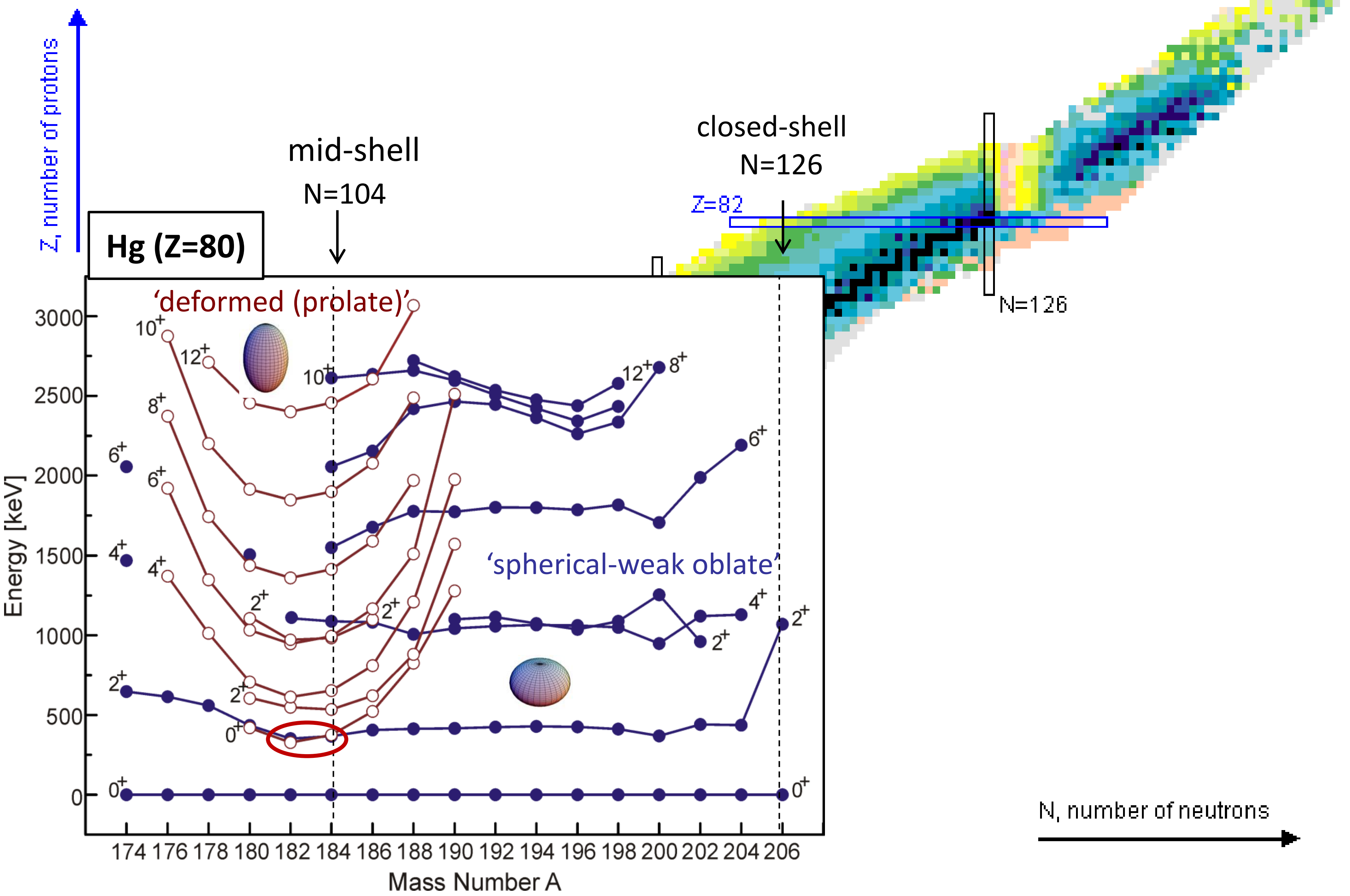
G. Ulm et al., Z.Phys. A325, 247 (1986)





B. A. Marsch et al., Nature Physics 14 (2018)

Shape coexistence around N=104 mid-shell



Hg (Z=80)

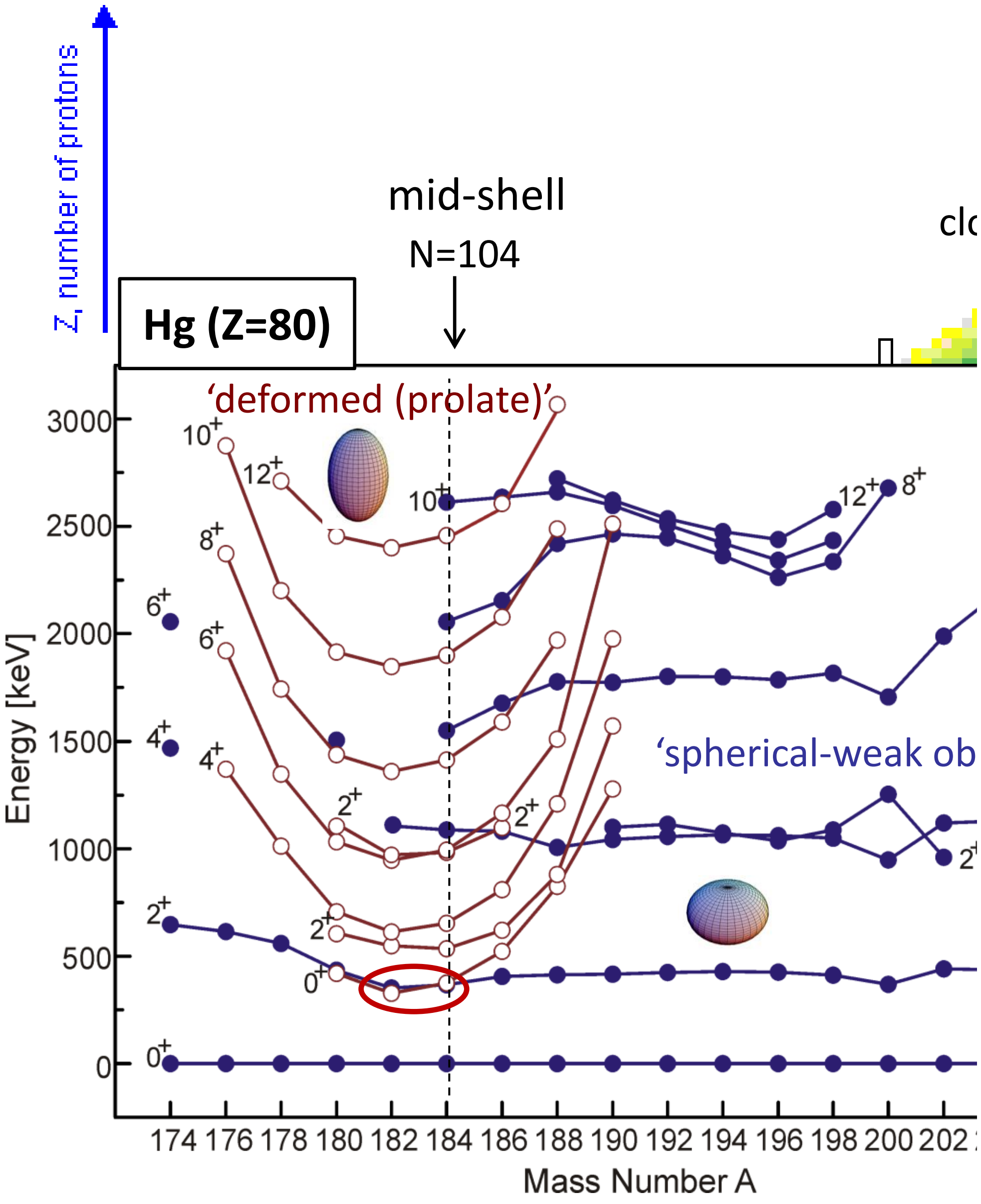
mid-shell N=104

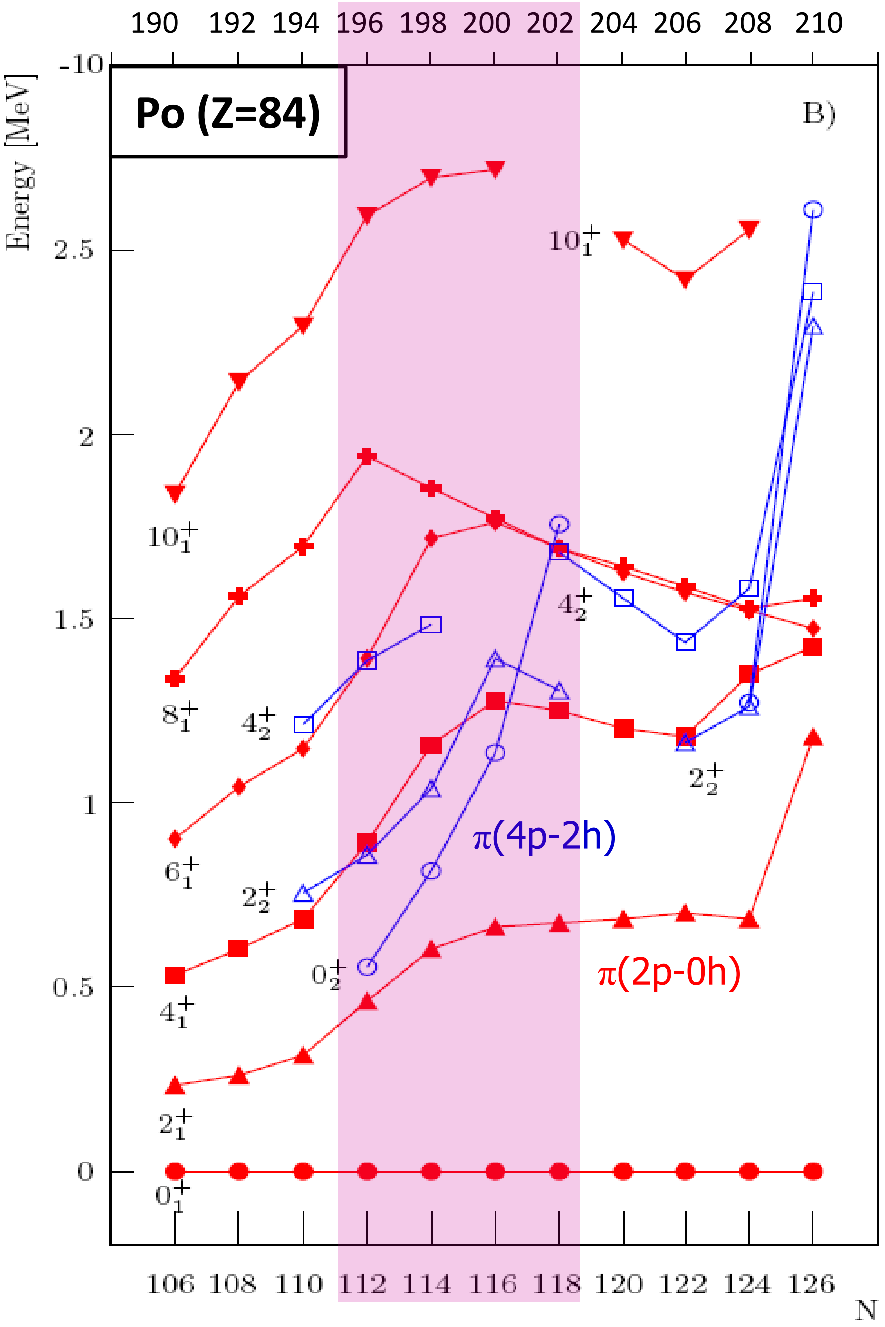
closed-shell N=126

'deformed (prolate)'

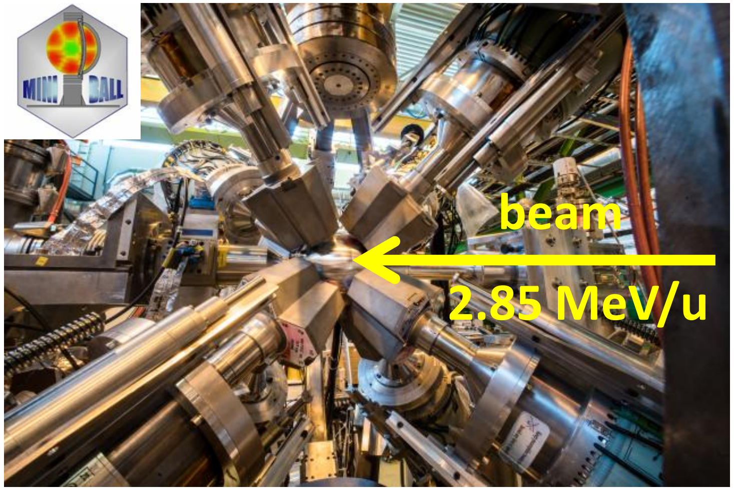
'spherical-weak oblate'

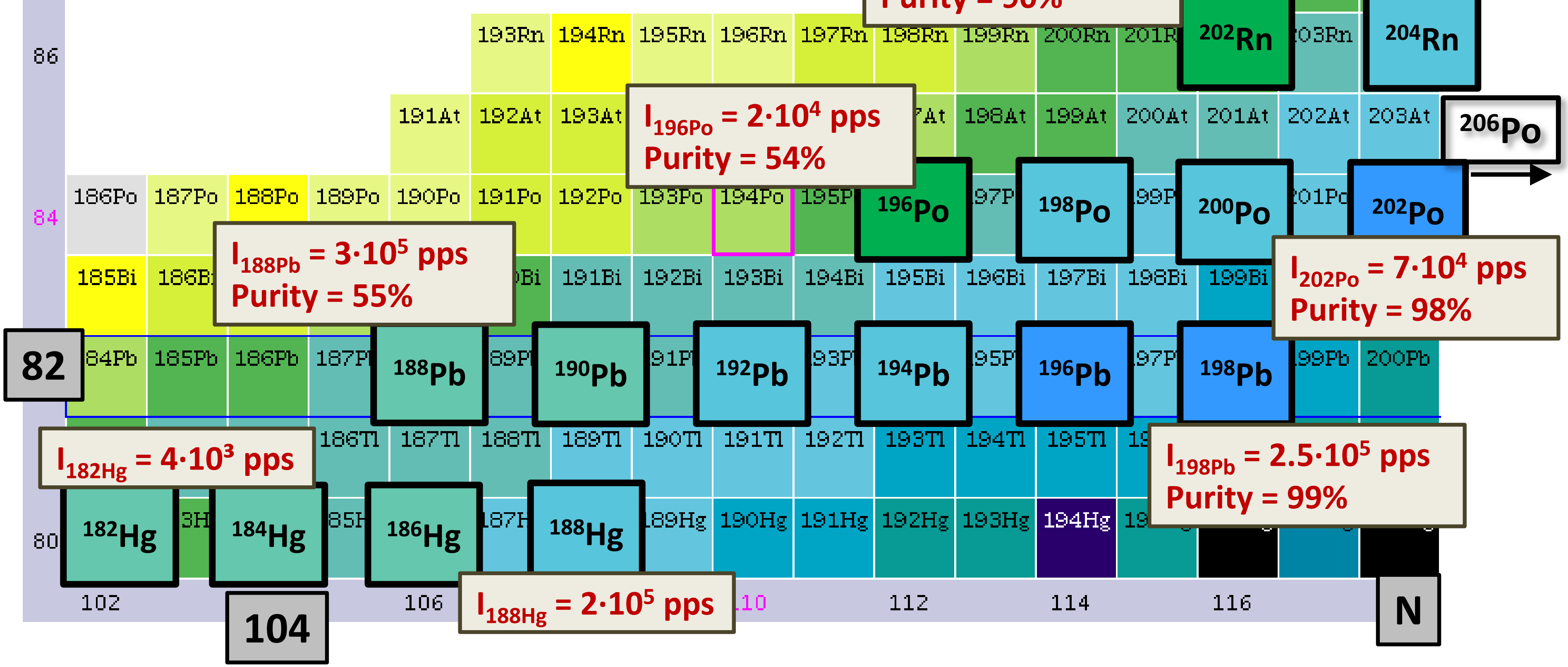
Shape coexistence





Coulex of Hg, Pb, Po, Rn exotic beams





$I_{202Rn} = 3 \cdot 10^4$ pps
Purity = 90%

$I_{204Rn} = 2 \cdot 10^5$ pps

$I_{196Po} = 2 \cdot 10^4$ pps
Purity = 54%

$I_{188Pb} = 3 \cdot 10^5$ pps
Purity = 55%

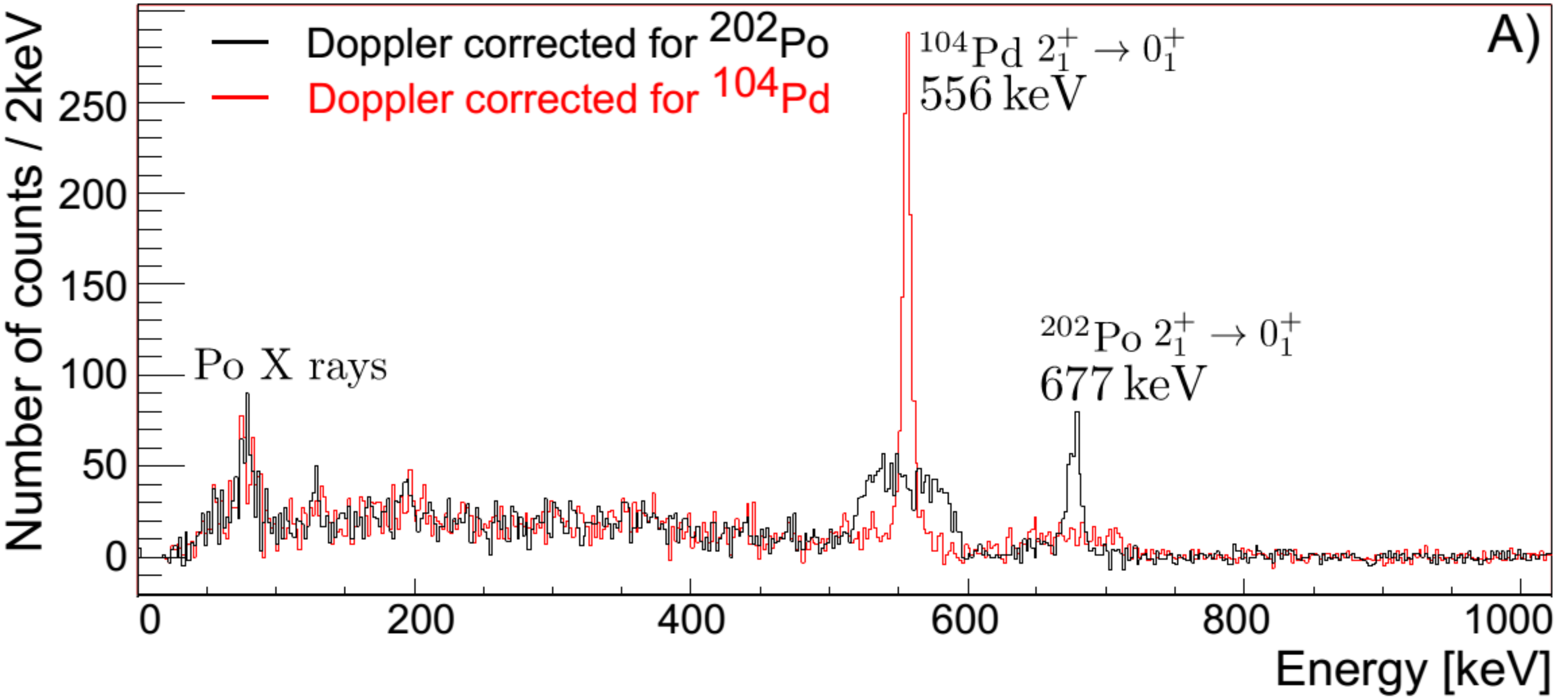
$I_{202Po} = 7 \cdot 10^4$ pps
Purity = 98%

$I_{182Hg} = 4 \cdot 10^3$ pps

$I_{198Pb} = 2.5 \cdot 10^5$ pps
Purity = 99%

$I_{188Hg} = 2 \cdot 10^5$ pps

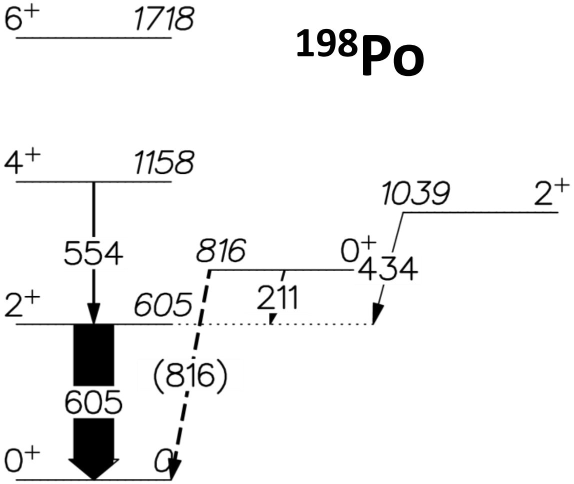
Coulomb excitation of even-even $^{196\text{-}202}$Po (Z=84):

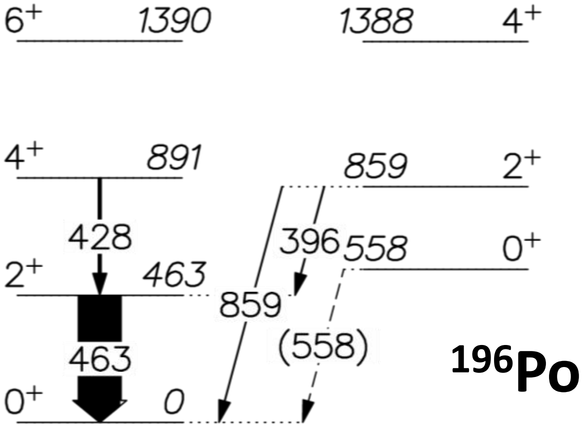


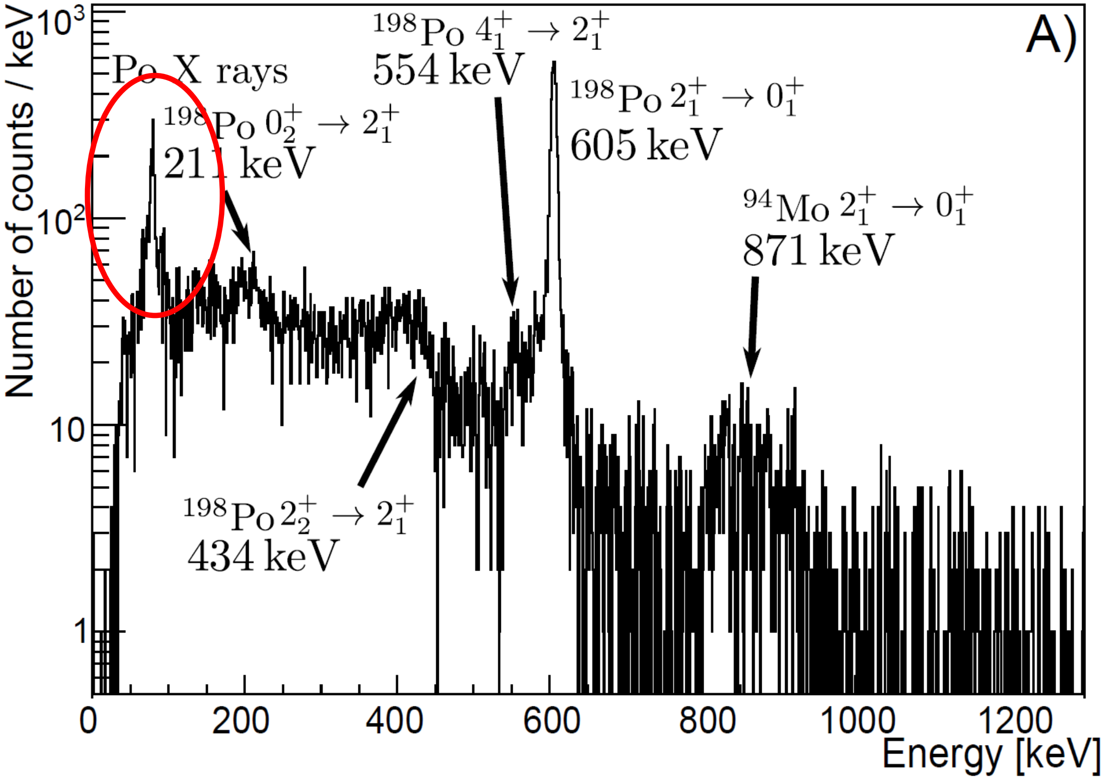
- Exclusive population of the 2^+_1 state in ^{200,202}Po

N. Kesteloot, PhD thesis KU Leuven 2015,
N. Kesteloot at el., PRC 92, 054301 (2015)

Coulomb excitation of even-even $^{196\text{-}202}$Po (Z=84):





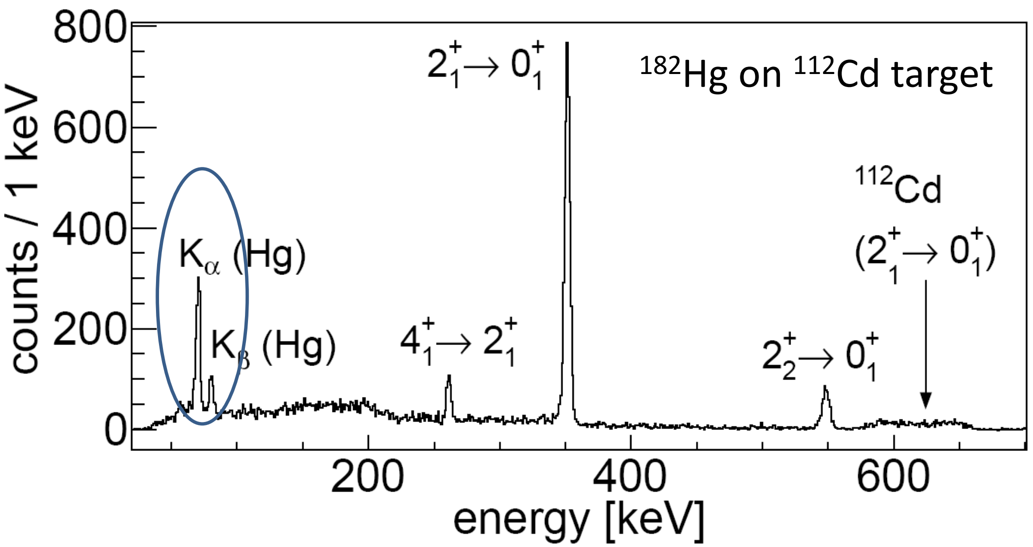


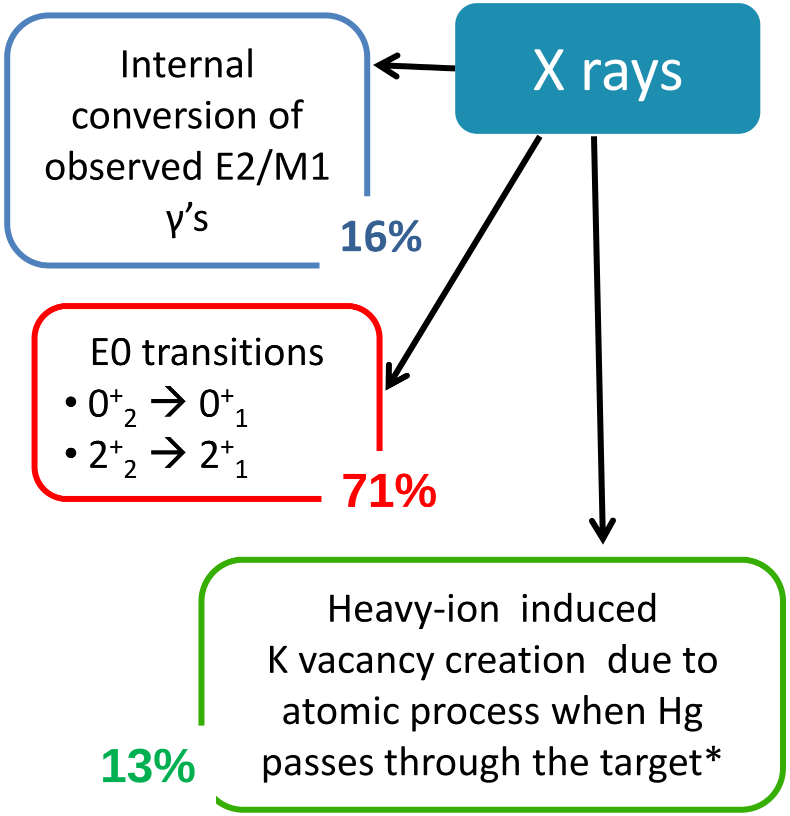
- Exclusive population of the 2^+_1 state in ^{200,202}Po
- Multi-step Coulex in ^{196,198}Po
- X rays → information on *E*0 transitions

N. Kesteloot, PhD thesis KU Leuven 2015,
N. Kesteloot at el., PRC 92, 054301 (2015)

The *E*0 transitions in ^{182,184}Hg:

N. Bree, KU Leuven, PhD thesis 2014
N. Bree et al., PRL 112, 162701 (2014)





X rays

Internal conversion of observed E2/M1 γ's

16%

E0 transitions
- $0^+_2 \rightarrow 0^+_1$
- $2^+_2 \rightarrow 2^+_1$

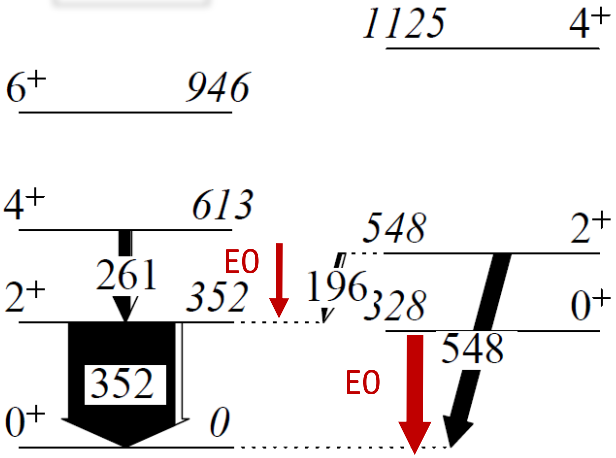
71%

Heavy-ion induced K vacancy creation due to atomic process when Hg passes through the target*

13%

*N. Bree, KWL, et al., NIM B 360 (2015) 97

^{182}Hg

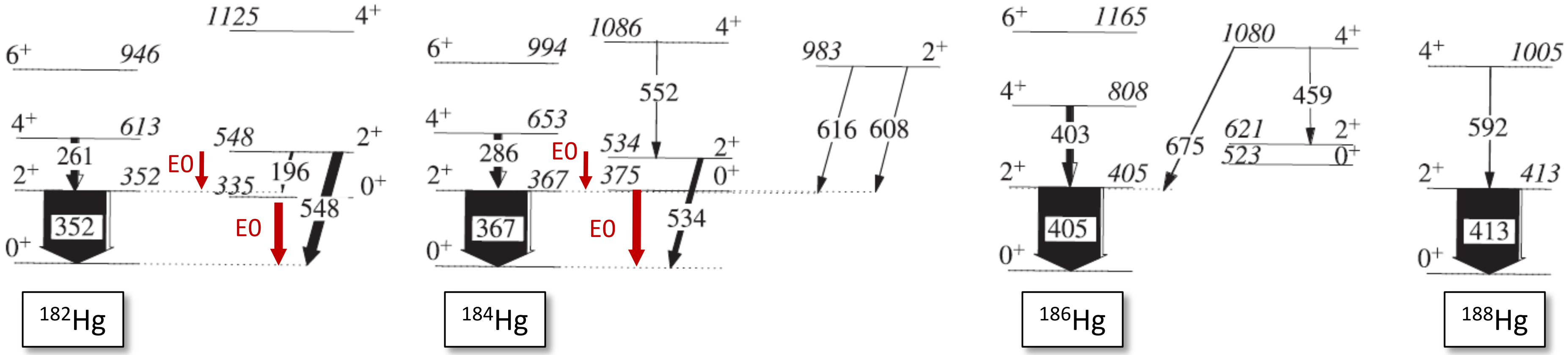


The $\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$ from β/EC decay of ^{182,184}Tl:

7.2 +/- 1.3 in **^{182}Hg** and **14.2 +/- 3.36** in **^{184}Hg**

E. Rapisarda et al., J. Phys. G: Nucl. Part. Phys. 44, 074001 (2017).

Coulomb excitation of even-even$^{182\text{-}188}$Hg (Z=80) @ 2.85 MeV/A:



γ ray intensities

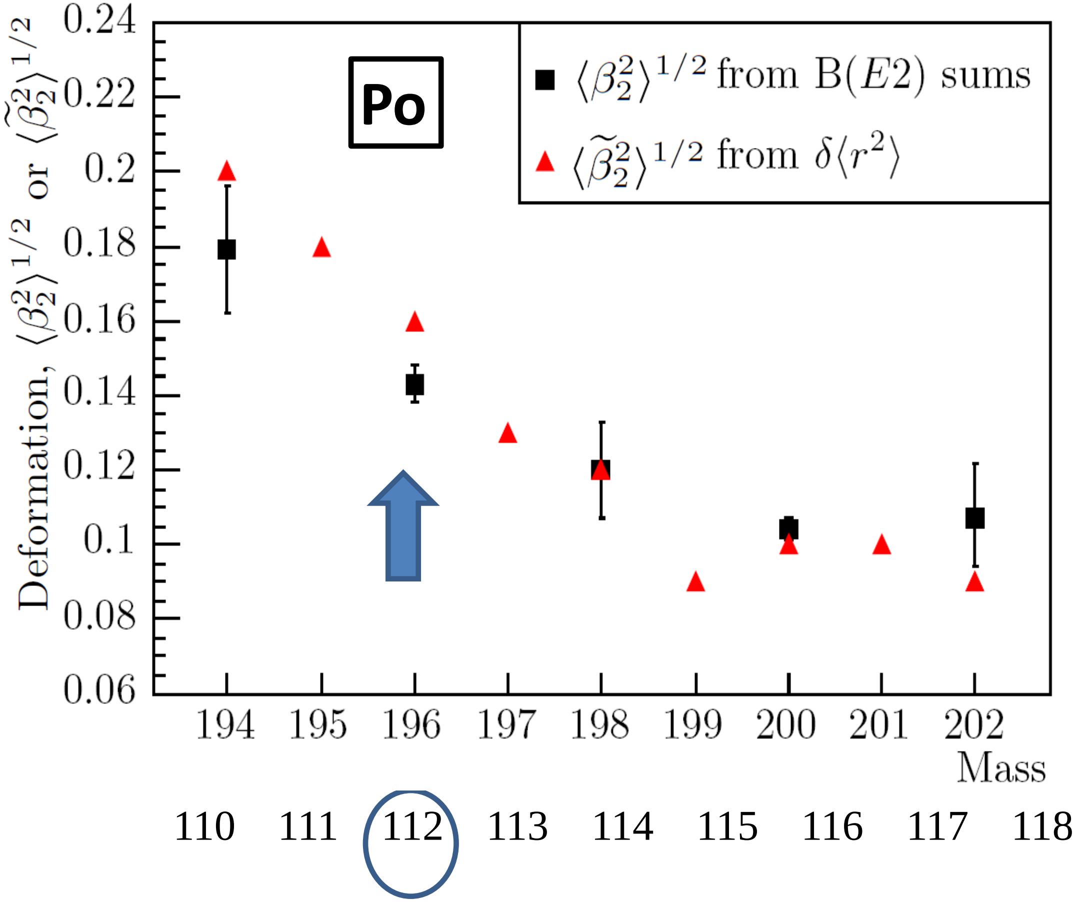
+ complementary data
e. g. **BR , τ,**
$\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$

GOSIA

matrix elements

Deformation of the ground state in Po isotopes:

$$\sum_i B(E2;0_1^+ \to 2_i^+) = \left(\frac{3}{4\pi}ZeR_0^2\right)^2 \langle\beta_2^2\rangle \qquad \langle r^2\rangle_A \approx \langle r^2\rangle_A^{\mathrm{sph}}\left(1+\frac{5}{4\pi}\langle\widetilde{\beta}_2^2\rangle_A\right)$$



<u>Laser spectroscopy mesurements:</u>

T. E. Cocolios et al.,
PRL 106, 052503 (2011)

M.D. Seliverstov et.al.,
PRC 89, 034323 (2014)

<u>Coulomb excitation:</u>

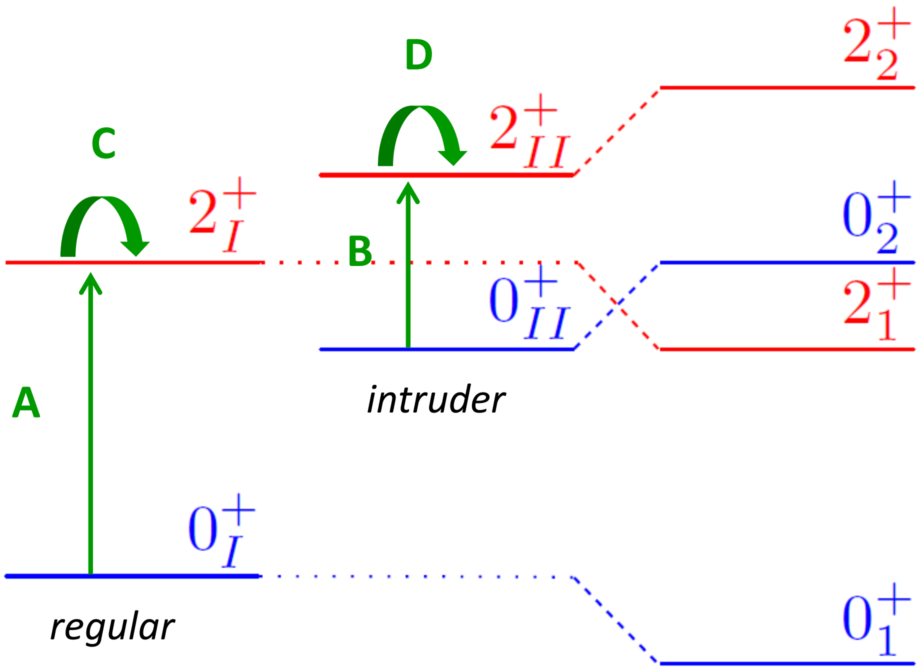
N. Kesteloot at el.,
PRC 92, 054301 (2015)

Two-state mixing model

P. Van Duppen , M. Huyse, J. Wood, J. Phys. G: Nucl. Part. 16, 441 (1990)

un-mixed configuration

mixed configuration



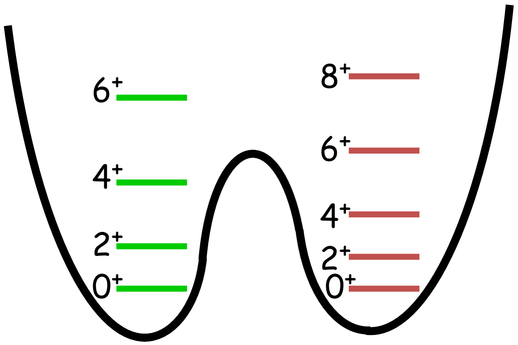
$$\begin{cases} |0^+_1\rangle = \alpha_0|0^+_I\rangle + \beta_0|0^+_{II}\rangle \\ |0^+_2\rangle = \beta_0|0^+_I\rangle - \alpha_0|0^+_{II}\rangle \\ |2^+_1\rangle = \alpha_2|2^+_I\rangle + \beta_2|2^+_{II}\rangle \\ |2^+_2\rangle = \beta_2|2^+_I\rangle - \alpha_2|2^+_{II}\rangle \end{cases}$$

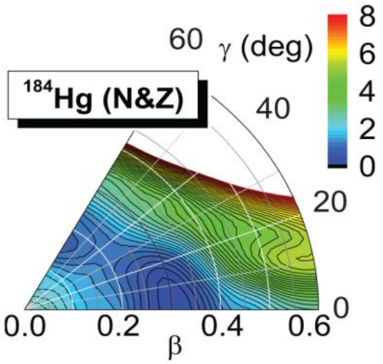
$$\alpha_J^2 + \beta_J^2 = 1$$

$$\langle J^\pi_I || E2 || J^\pi_{II} \rangle = 0$$

E2 matrix elements can be expressed by:

- un-mixed E2 matrix elements → **A, B, C, D**
- mixing amplitudes ($\alpha_0, \alpha_2, \beta_0, \beta_2$)





$$\begin{cases} \langle 0^+_1|E2|2^+_1\rangle = \alpha_0\,\alpha_2\mathbf{A} + \beta_0\,\beta_2\mathbf{B} \\ \langle 0^+_1|E2|2^+_2\rangle = \alpha_0\,\beta_2\mathbf{A} - \beta_0\,\alpha_2\mathbf{B} \\ \langle 0^+_2|E2|2^+_1\rangle = \alpha_2\,\beta_0\mathbf{A} - \alpha_0\,\beta_2\mathbf{B} \\ \langle 0^+_2|E2|2^+_2\rangle = \beta_0\,\beta_2\mathbf{A} + \alpha_0\,\alpha_2\mathbf{B} \\ \langle 2^+_1|E2|2^+_2\rangle = \alpha_2\,\beta_2\,(\mathbf{C}-\mathbf{D}) \end{cases}$$

J. M. Yao et al., Phys. Rev. C 87 (2013) 034322

Mixing amplitudes

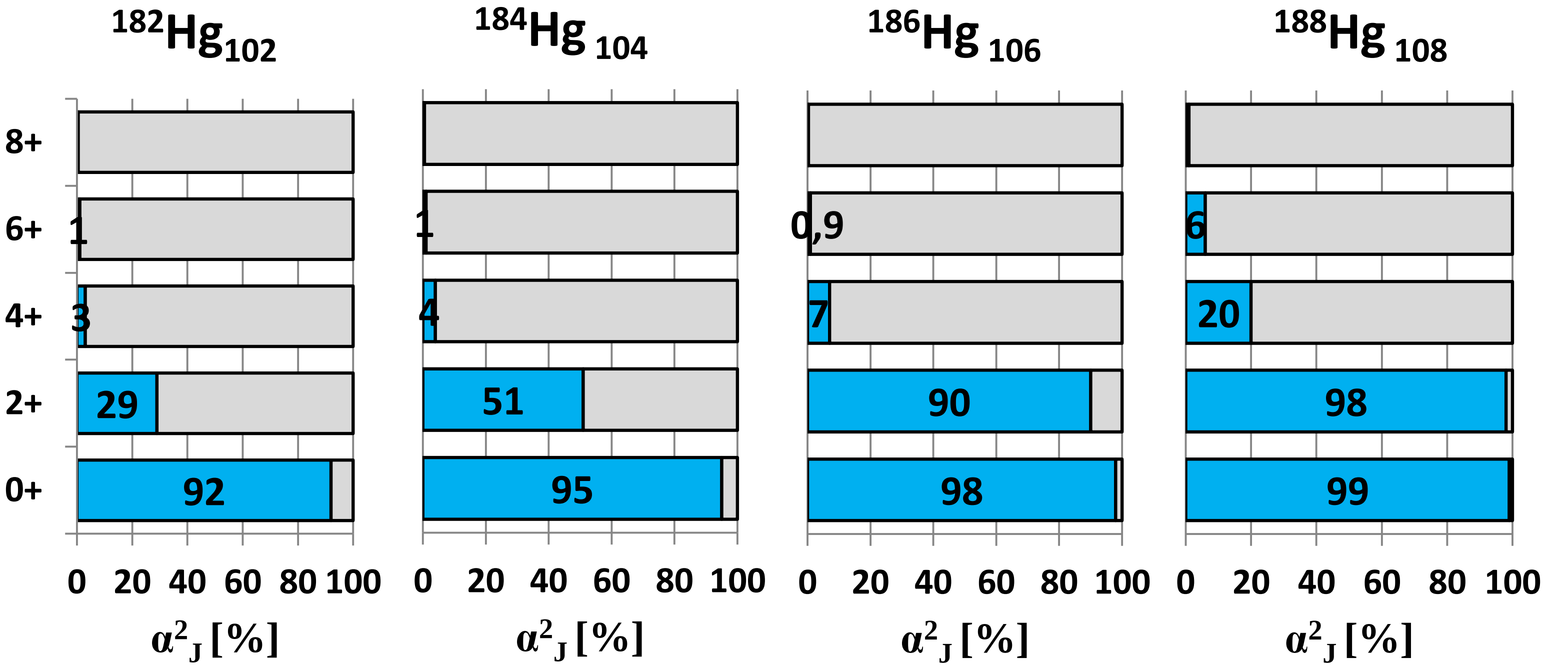
From the fit of the known higher-lying level energies in the rotational bands, built upon the $0^+_{gs,2}$ states, using the variable moment of inertia (VMI) model:

L.P. Gaffney et al, PRC 89, 024307 (2014)

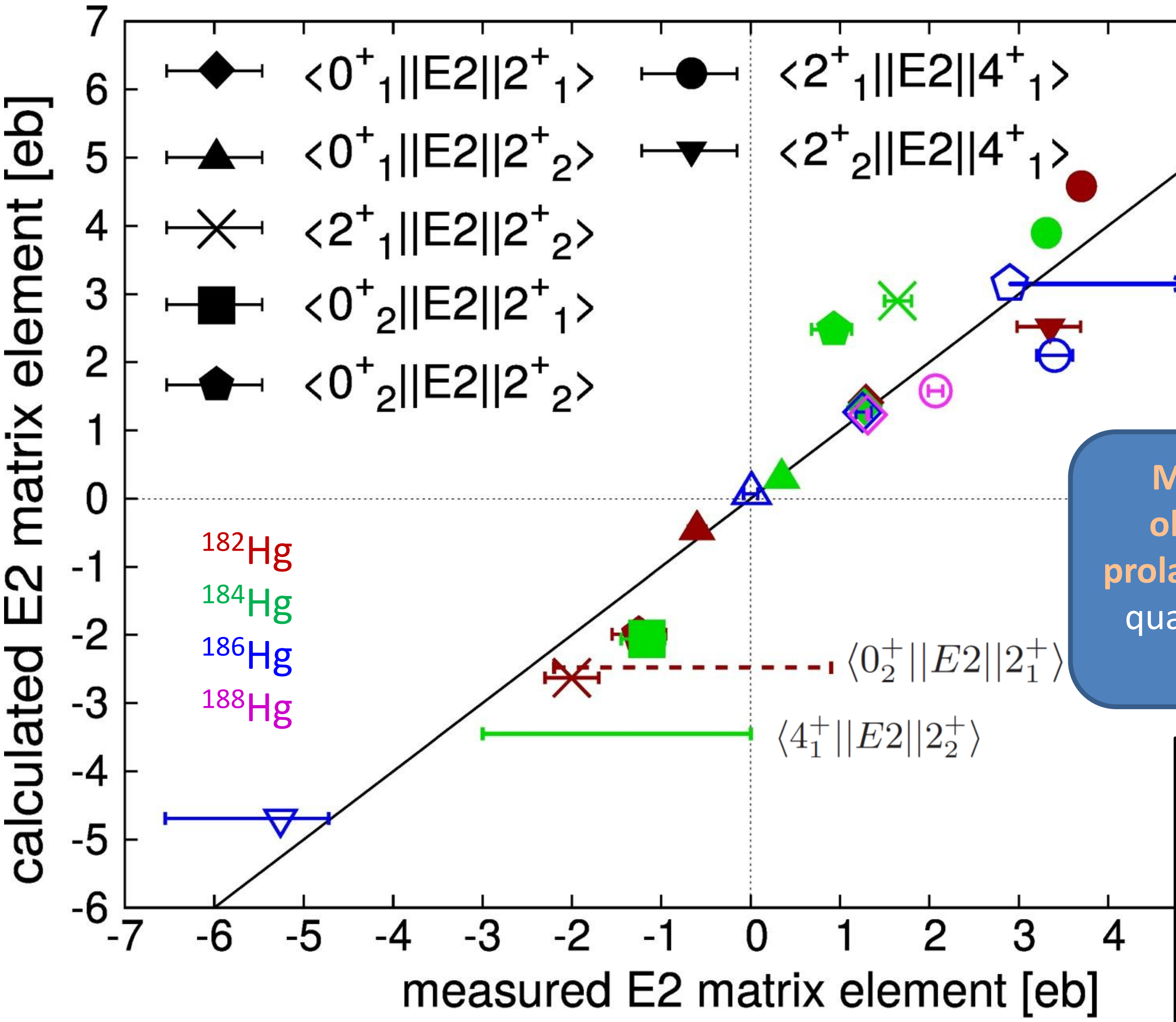
	α_{0+}^2	α_{2+}^2	α_{4+}^2
$^{182}Hg_{102}$	92%	**29%**	3%
$^{184}Hg_{104}$	95%	**51%**	4%
$^{186}Hg_{106}$	98%	**90%**	7%
$^{188}Hg_{108}$	99%	**98%**	20%

N. Kesteloot et al, PRC 92, 054301 (2015)

	α_{0+}^2	α_{2+}^2
$^{194}Po_{110}$	12%	**29%**
$^{196}Po_{112}$	85%	**50%**
$^{198}Po_{114}$	94%	**69%**
$^{200}Po_{116}$	97%	**92%**
$^{202}Po_{118}$	99%	**88%**



Interpretation with two-level mixing model



	α_{0+}^2	α_{2+}^2	α_{4+}^2
^{182}Hg	92%	**29%**	3%
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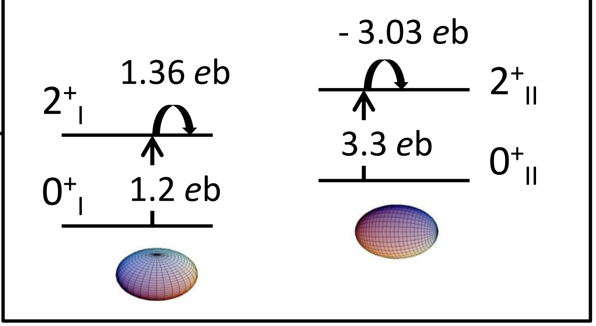
^{186}Hg	98%	**90%**	7%
^{188}Hg	99%	**98%**	20%

L.P. Gaffney et al, PRC 89, 024307 (2014)

Mixing between less-deformed **oblate-like** and more-deformed **prolate-like** configurations, with their quadrupole properties assumed to be constant for all $^{182-188}$Hg

un-mixed *ME2*'s and Q_s:



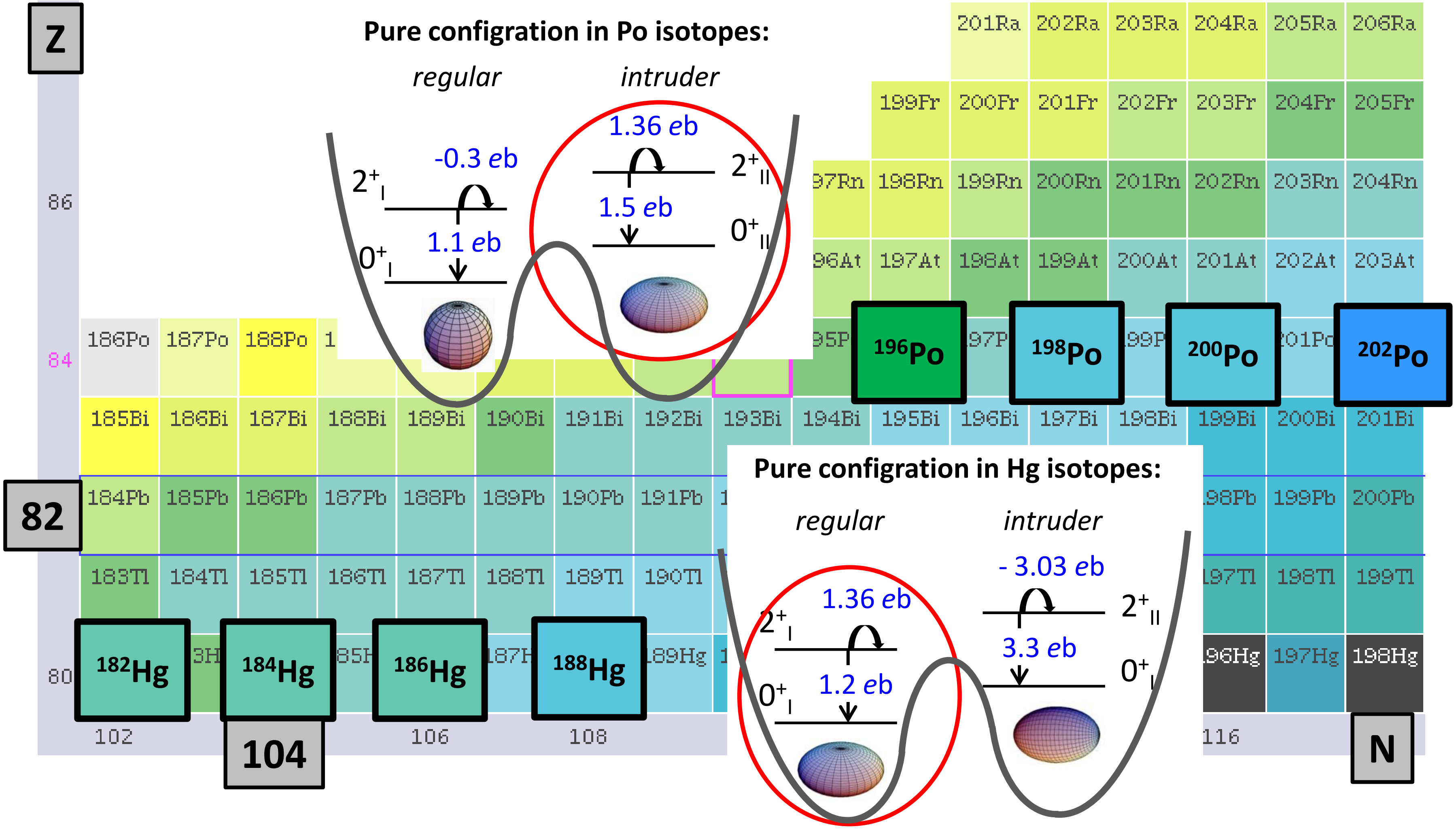
N. Bree et al., PRL 112, 162701 (2014) K. Wrzosek-Lipska et al., submitted to PRC

Mixing of coexisting shapes in light Po and Hg isotopes

Po:

- ➢ mixing of a **spherical** structure with a **weakly deformed oblate** structure;
- ➢ experimental results support the interpretation that a weakly deformed, oblate structure is intruding in the low-lying energy levels.

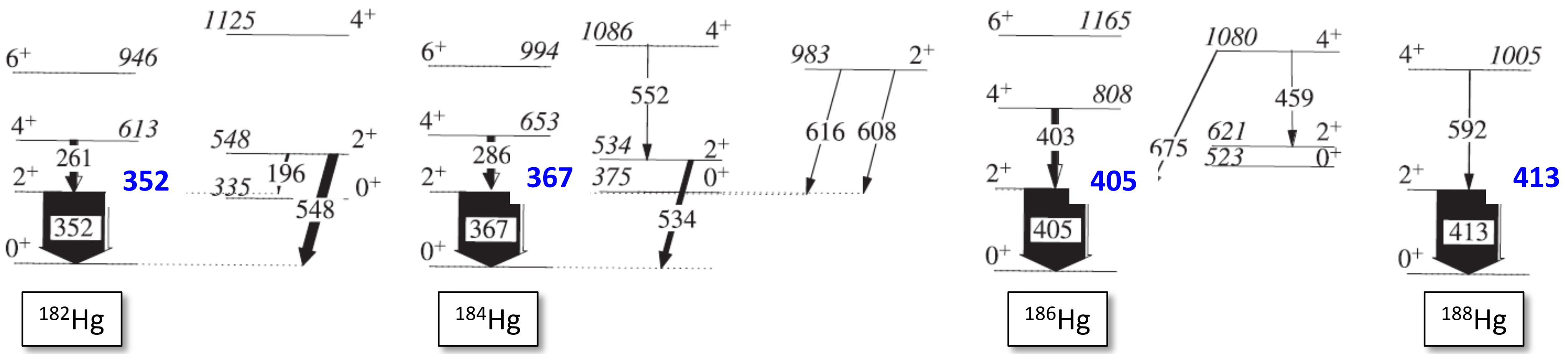
N. Kesteloot at el., PRC **92**, 054301 (2015)



Pure configration in Po isotopes:

Pure configration in Hg isotopes:

Concealed configuration mixing in the light Hg isotopes



Similar **$E(2^+_1)$**, **$B(E2;\ 2^+_1 \rightarrow 0^+_1)$**, do not always reveal a similar structure !

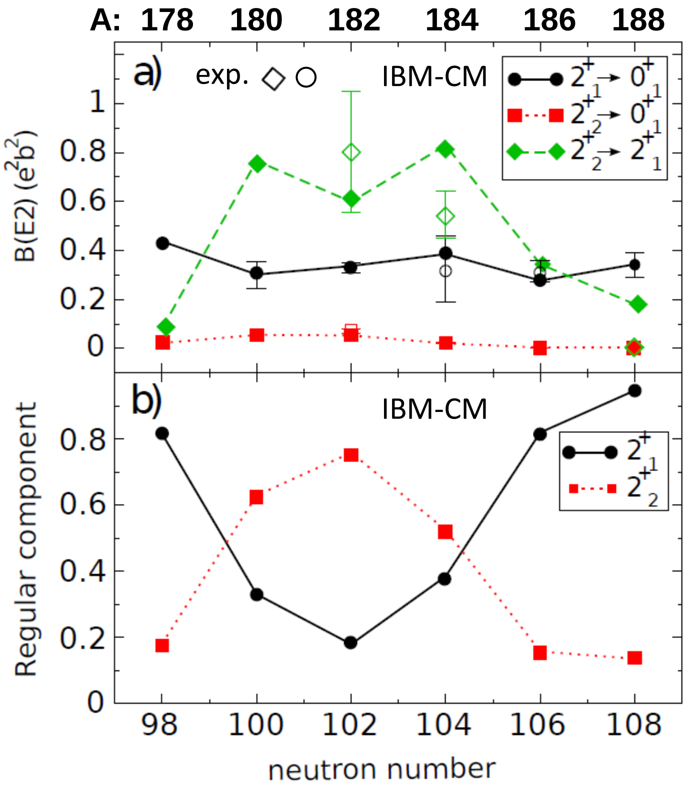
→ a **dramatic change** of the **underlying configuration of the** 2^+_1's: from the pure **regular** (**^{186,188}Hg**) to dominated by **intruder** character (**^{182}Hg**).

The underlying mixing configuration is somehow ***concealed***

The same concluded for the **Pt isotopes**

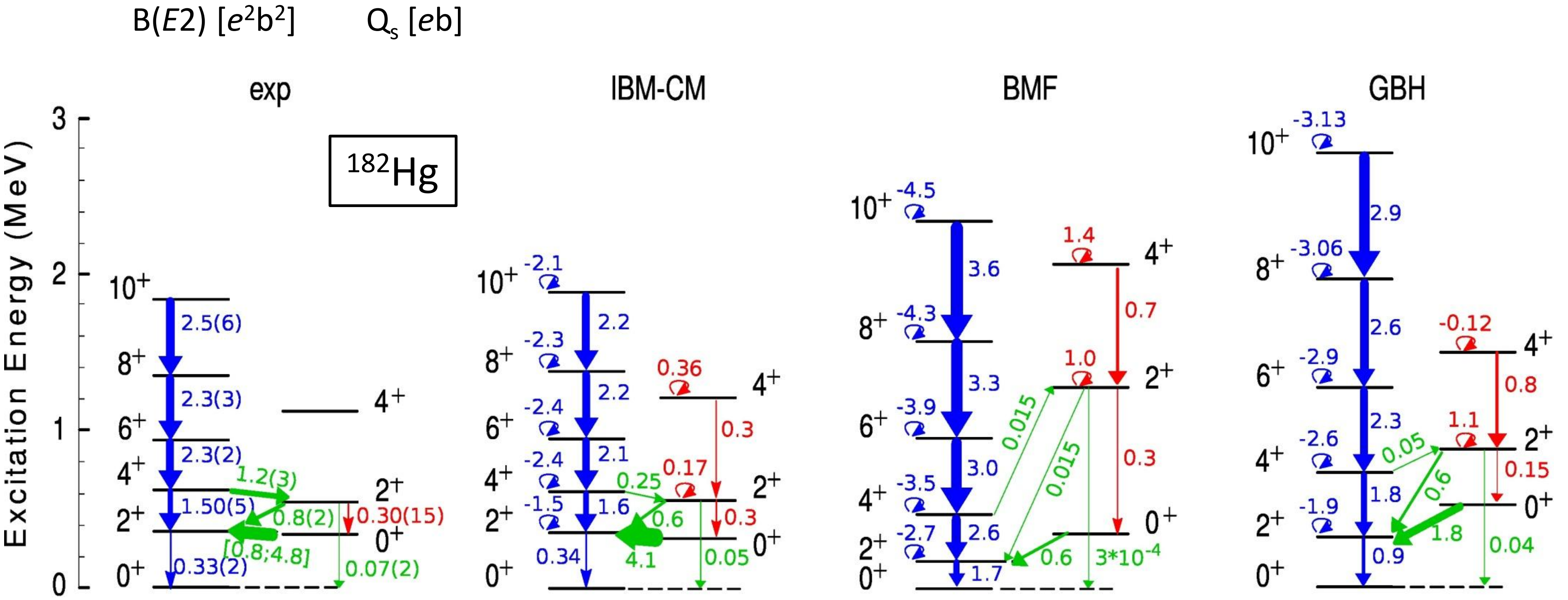
→ there mixing occures at the level of the **0^+** state

J. E. García-Ramos, V. Hellemans, and K. Heyde PRC 84, 014331 (2011)



IBM-CM calculations: J. E. Garcia-Ramos, K. Heyde

Comparison with theory



Coulex, ISOLDE, CERN

K. Wrzosek-Lipska et al.,
submitted to PRC

N.Bree, KWL et al,
PRL 112, 162701 (2014)

+

RDDS measurement

L. P. Gaffney et al.,
PRC 89, 024307 (2014).

IBM + configuration mixing:

J.E. Garcia-Ramos, K. Heyde
PRC 89, 014306 (2014)

BMF: HFB+GCM+SLy6:

J.M. Yao, M. Bender, P.-H. Heenen
PRC 87, 034322 (2013)

GBH: ATD HFB + SLy4:

L. Próchniak, priv. comm.

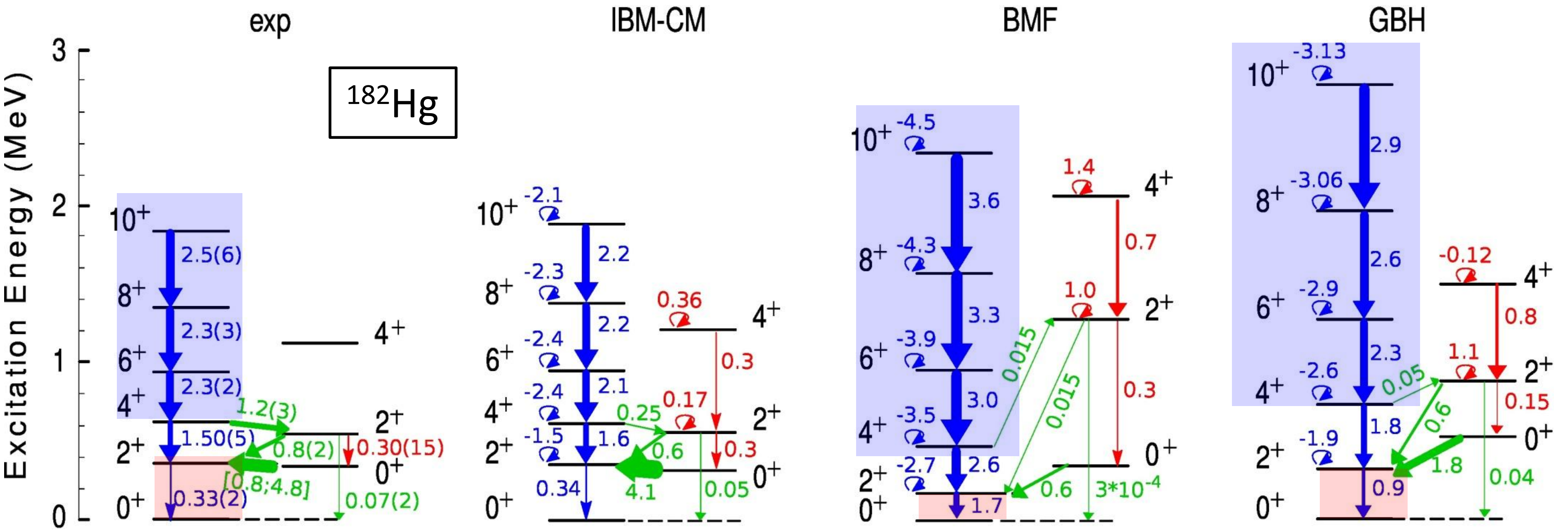
Comparison with theory

B(E2) [e^2b^2]   Q$_s$ [eb]

J. E. Garcıa-Ramos and K. Heyde, PRC 89, 014306 (2014)

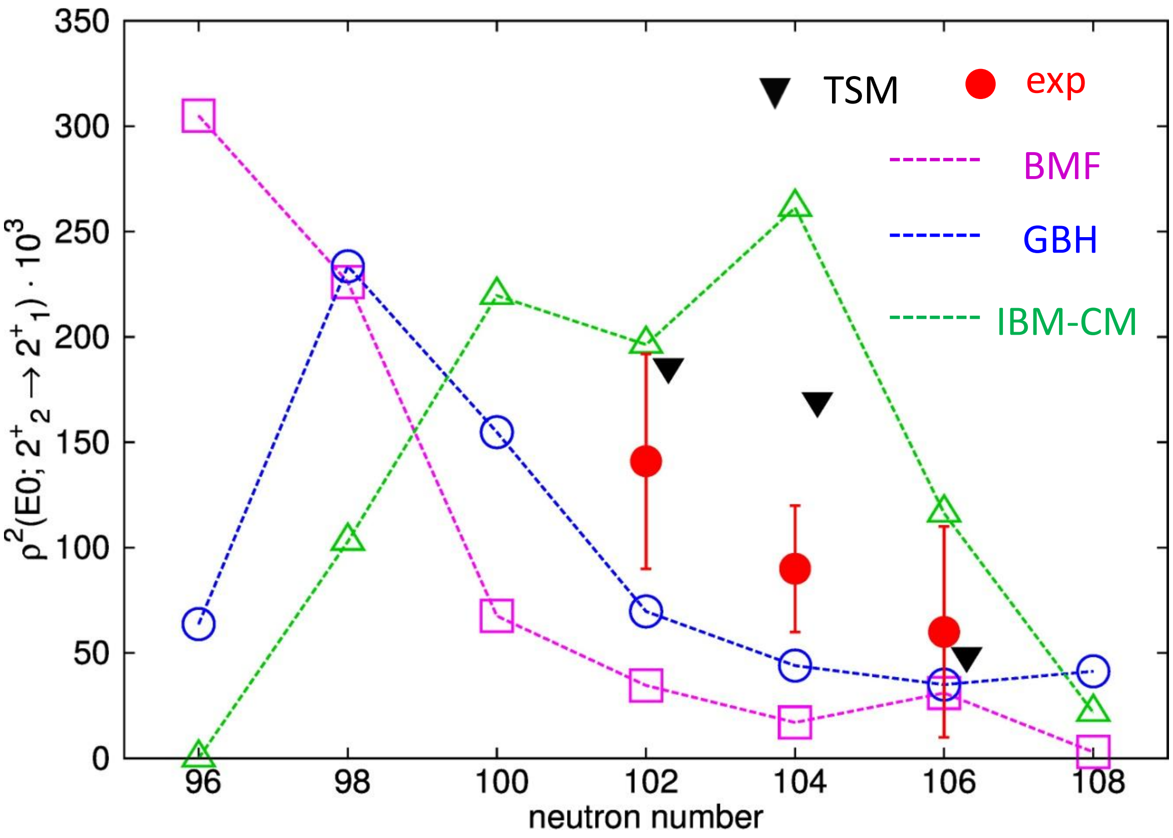
J. M. Yao, M. Bender and P. H. Heenen, PRC 87, 034322 (2013)

L. Próchniak, priv. comm.



1. GBH and BMF: **energy spectra are too spread out** compared to the experimental data.
2. The IBM-CM, GBH and BMF Q_{sp} values of yrast states are negative → predominantly **prolate** configuration.
3. BMF: crossing between prolate and oblate configuration between N=106 and N=108 ;
   for the IBM-CM this transition happens at N=104.
3. Smooth behavior of the experimental B(E2) values for states with spin J ≥ 4.
4. This trend, as well as the absolute B(E2) values, are fairly well reproduced by the GBH and BMF.
5. For the low-lying 2$^+$ and 0$^+$ states the comparison with theory is less successful.

Monopole transition strength



Experimantal values:

^{182,184}Hg:

from B(E2; $2^+_2 \rightarrow 2^+_1$) and $\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$

^{186}Hg:

M. Scheck et al., PRC 83, 037303 (2011)

TSM: two-state mixing model:

$$\rho^2(E0) = \frac{Z^2}{R_0^4}\cdot\alpha^2(1-\alpha^2)\left[\Delta\langle r^2\rangle\right]^2$$

IBM-CM: *J. E. Garcıa-Ramos and K. Heyde,*
PRC 89, 014306 (2014)

BMF: *J. M. Yao, M. Bender, and P. H. Heenen,*
PRC 87, 034322 (2013)

GBH: *L. Próchniak, priv. com.*

- The **rising trend** of the experimental $\rho^2(E0)$'s **towards the lighter mercury isotopes**.
- The same trend is reproduced by the BMF and GBH calculations.
- Both BMF and GBH models indicate **similar magnitudes of the $\rho^2(E0)$** especially ~ N = 104.
- It is different from the IBM-CM predictions and TSM calculations → **largest $\rho^2(E0)$ around N=104.**

Future experiments:

IS566:

Probing intruder configurations in ^{186,188}**Pb**
using **Coulomb excitation**

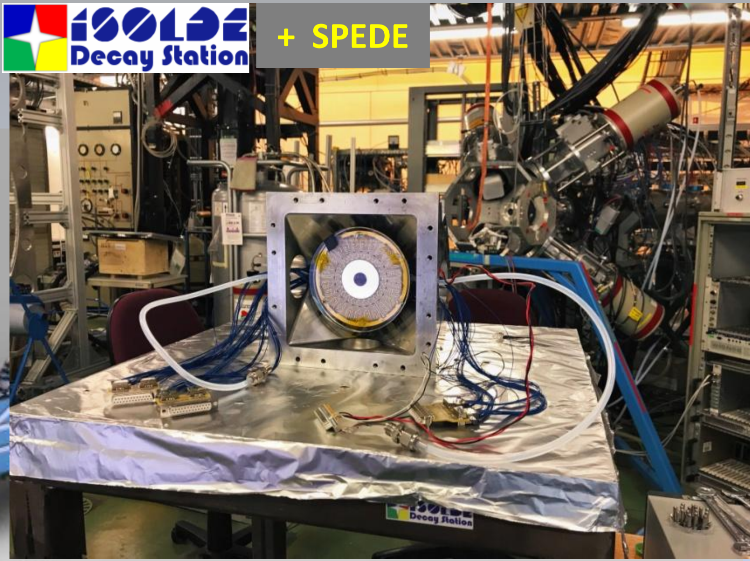
IS563:

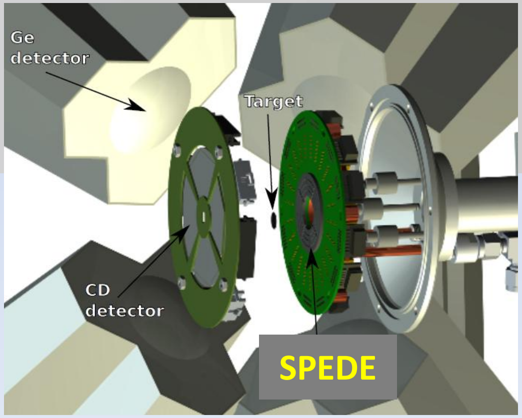
Couloumb excitation of ^{182}**Hg** and ^{184}**Hg**: Shape coexistence in the neutron-deficient lead region

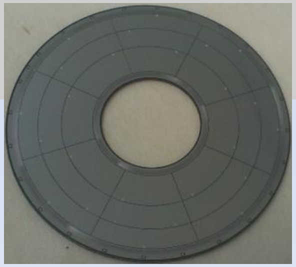
with HIE-ISOLDE, Miniball and SPEDE

IS641: Oct. 2018

Decay spectroscopy of ^{182,184,186}**Hg**
studied in **β-decay** of Tl with
IDS (Isolde Decay Station)







P. Papadakis et al., Eur.Phys.J. A 54, 42 (2018)
J. Konki et al., EPJ Web of Conference 63, 01019 (2013).

Summary:

1. The electromagnetic properties of even-even $^{182-188}$**Hg** were described in terms of **mixing** of two pure structures: less-deformed **oblate** (*regular*) and more-deformed **prolate** (*intruder*) which **coexist** at low-excitation energy.

2. Even-even $^{196-202}$**Po** : **mixing** of coexisting **spherical** structure with a weakly deformed **oblate** structure .

3. ***Concealed*** configuration mixing in Hg isotopes – similar level energies and transition probabilities in an isotopic chain do not always reveal a similar structure!

4. Partial agreement between theoretical models and experimental results.

☐ Continuation of Coulex studies with higher energy beams **4 MeV/A** at **HIE-ISOLDE:**

- increase sensitivity of subtle second order effects, i.e. Q_s moments of the excited states;
- establish the deformation of the intruder 0^+ states;
- probing higher-lying non-yrast states.

☐ Crucial role of the complementary data: γ-ray **BR** ratios, **τ**, **δ**($E2/M1$), $\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$.

☐ **SPEDE** (**Sp**ectrometer for **E**lectron **De**tection) will provide a direct way of detecting the $E0$ transitions.

Thank you for your attention!

Special thanks to:

P. Van Duppen (KU Leuven)
M. Huyse (KU Leuven)
N. Bree (PhD KU Leuven)
N. Kesteloot (PhD KU Leuven)
K. Rezynkina (KU Leuven)
L. P. Gaffney (Cern)
M. Zielińska (CEA Saclay)
J. L. Wood (Georgia Inst. of Tech. Atlanta)
M. Bender (IPNL Lyon Univ.)
P. H. Heenen (Brussel Univ.)
J.E. García-Ramos (Huelva Univ.)
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