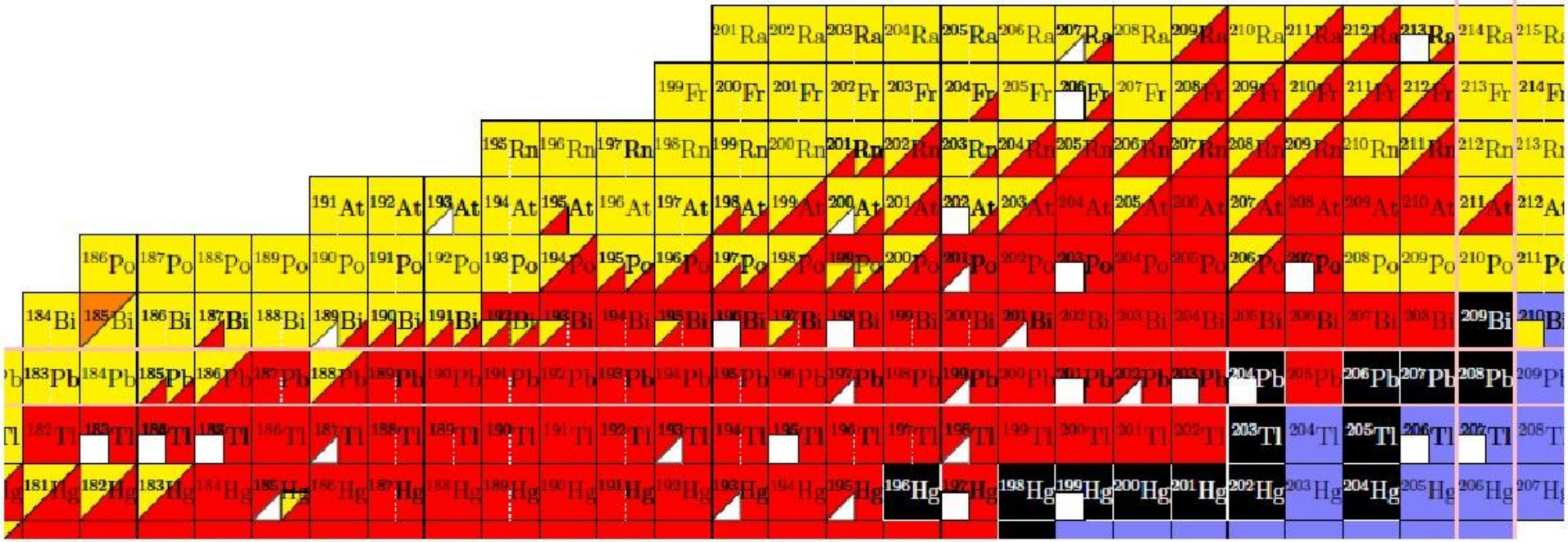
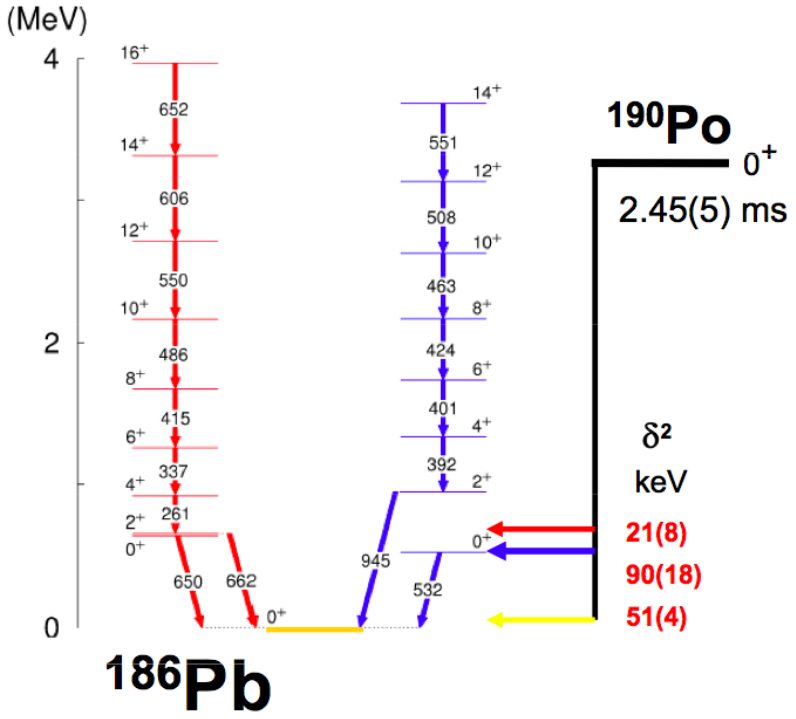
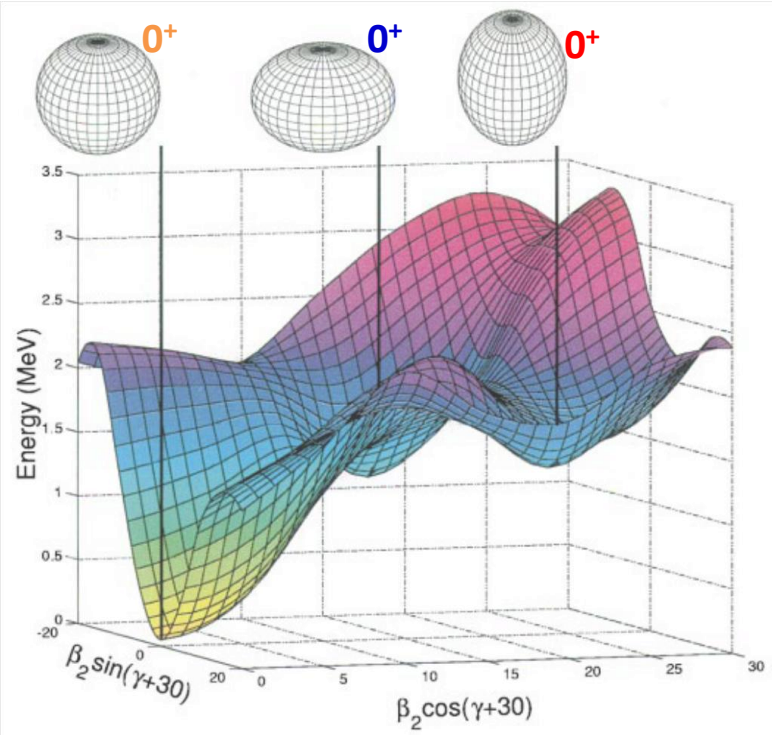


The observation of a strong E0 component in the $2^+ \rightarrow 2^+$ transition in ^{184}Hg from the β-decay of laser-ionized thallium isotopes: a strong signature of shape-coexistence

Elisa Rapisarda

A classical example: ^{186}Pb



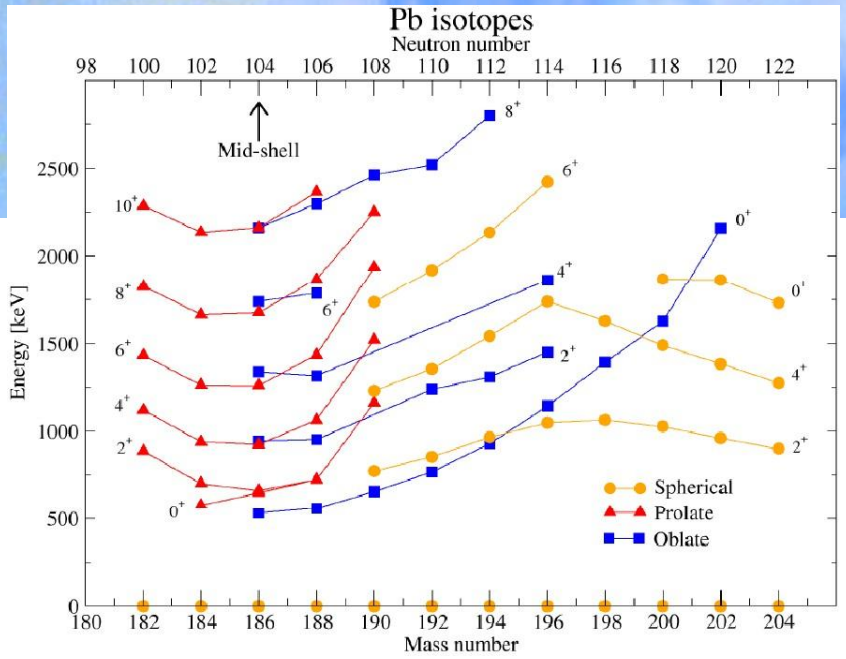


A.N. Andreyev et al., Nature 405(2000)430

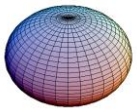
- Shape coexistence = proximity of spherical and/or deformed shapes(s) at low energy (E < few MeV)
- ^{186}Pb: most dramatic examples where the three lowest lying states are 0+ states of three different shapes within less than 700 keV.

Shape coexistence

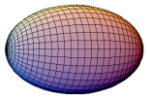
in Hg isotopes



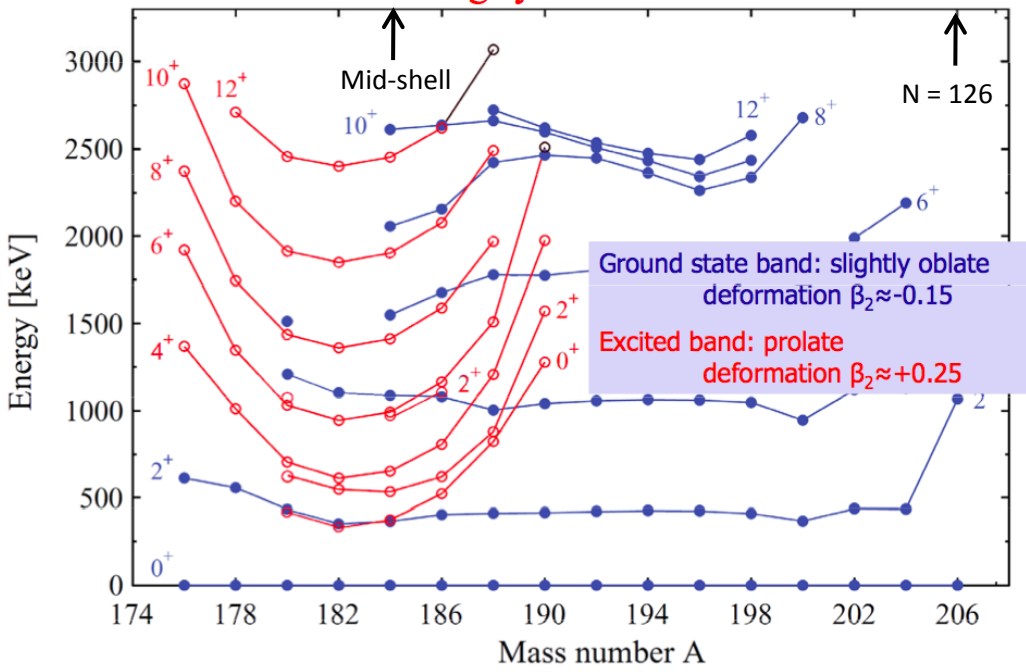
slightly oblate ground state band



excited prolate band



Even Hg systematics

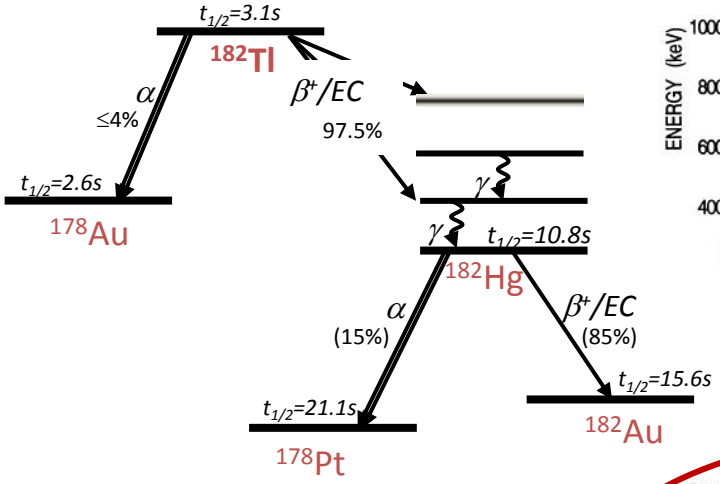


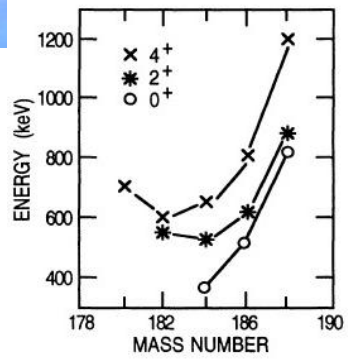
Evidence for shape coexistence in systematic energy levels: flat behaviour of the spherical states against parabolic intrusion of the deformed states with a minimum at mid-shell N = 104.

Common indication of shape coexistence in nuclei

β-decay spectroscopy

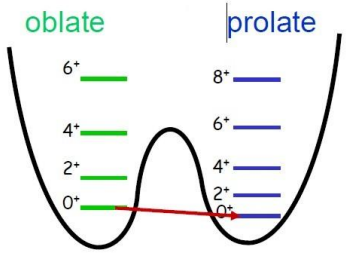
[1] K.S. Bindra et al.,
Phys. Rev. C, 51 (1995) 401





KEY FEATURES

- Decay dominated by selection rule:
  $\Delta I = \pm 1,0$
- low-lying non-yrast coexisting states
- E0 component of intraband transition



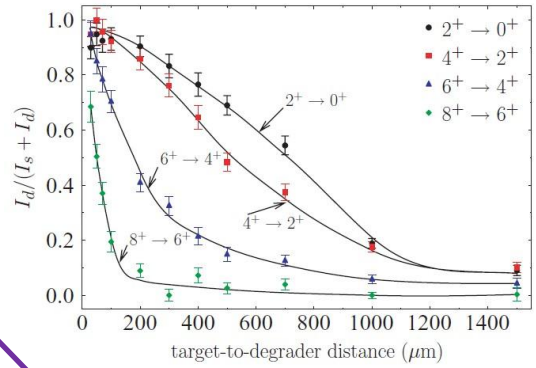
E0 component

Spectroscopy methods

What are the observables (“*Shape coexistence in atomic nuclei*”, K.Heyde and J.Wood, Rev.Mod.Phys., Vol.83, n.4 (2011) 1467

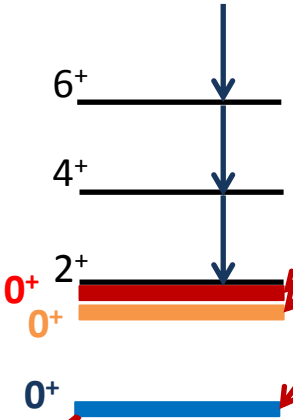
^{182}Tl ^{182}Hg ^{186}Pb ^{190}Po

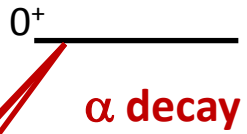
in beam



T. Grahn et al.
PRC80(2009) 014324

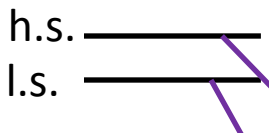
J. Heese et al.
PLB302(1993) 390



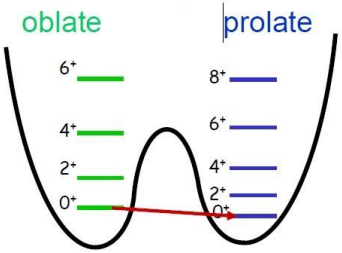


α decay

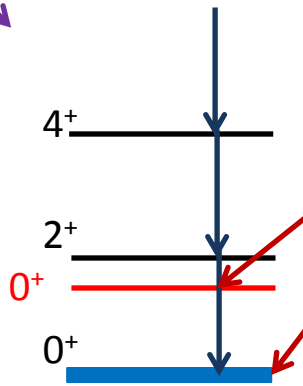
A. Andreyev et al.
Nature 405 (2000) 430



β decay



E0 component



Coulex

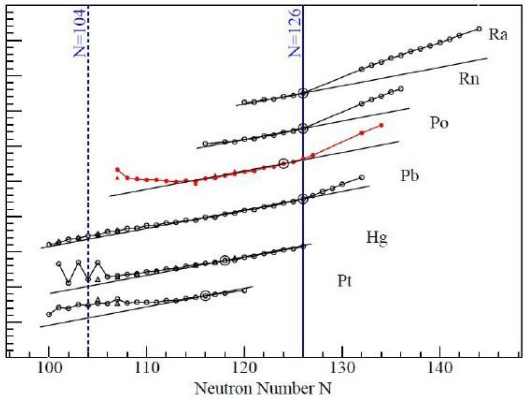
N. Bree & A. Petts

Transfer reactions

Ground State properties

Mass measurements (direct, α decay)

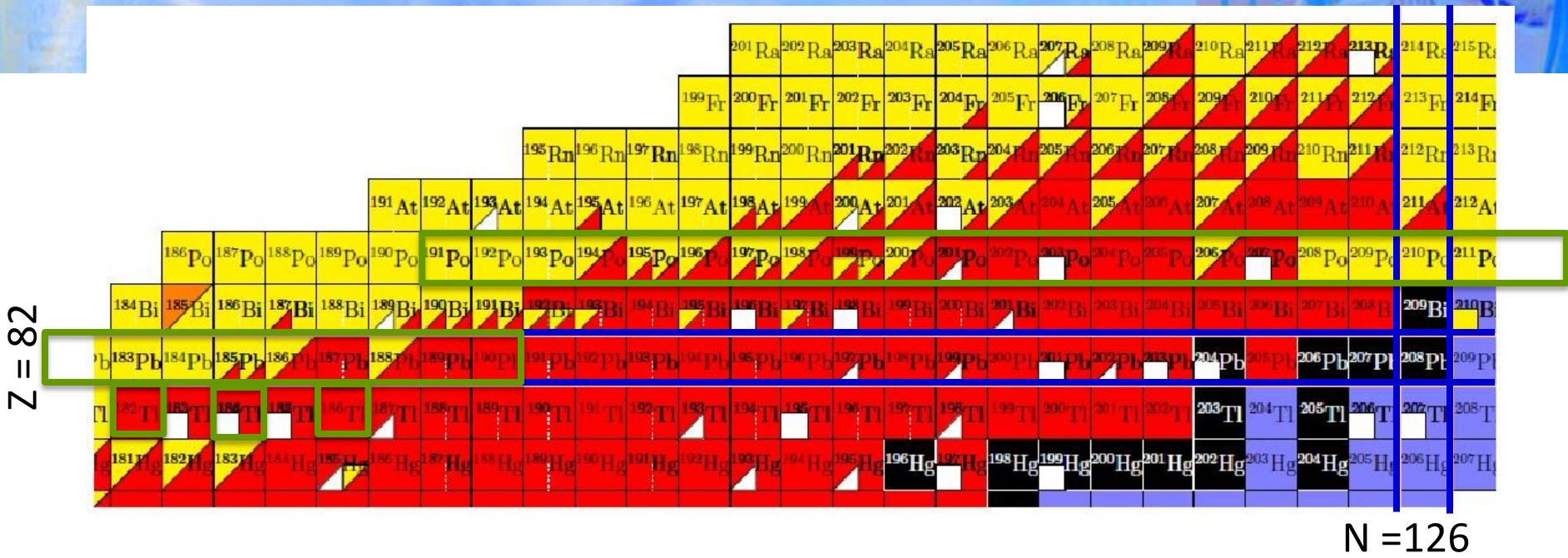
Laser Spectroscopy



T. Cocolios et al. PRL106(2011) 052503
H. De Witte et al. PRL98(2007) 112502

Overview

What is going on the region

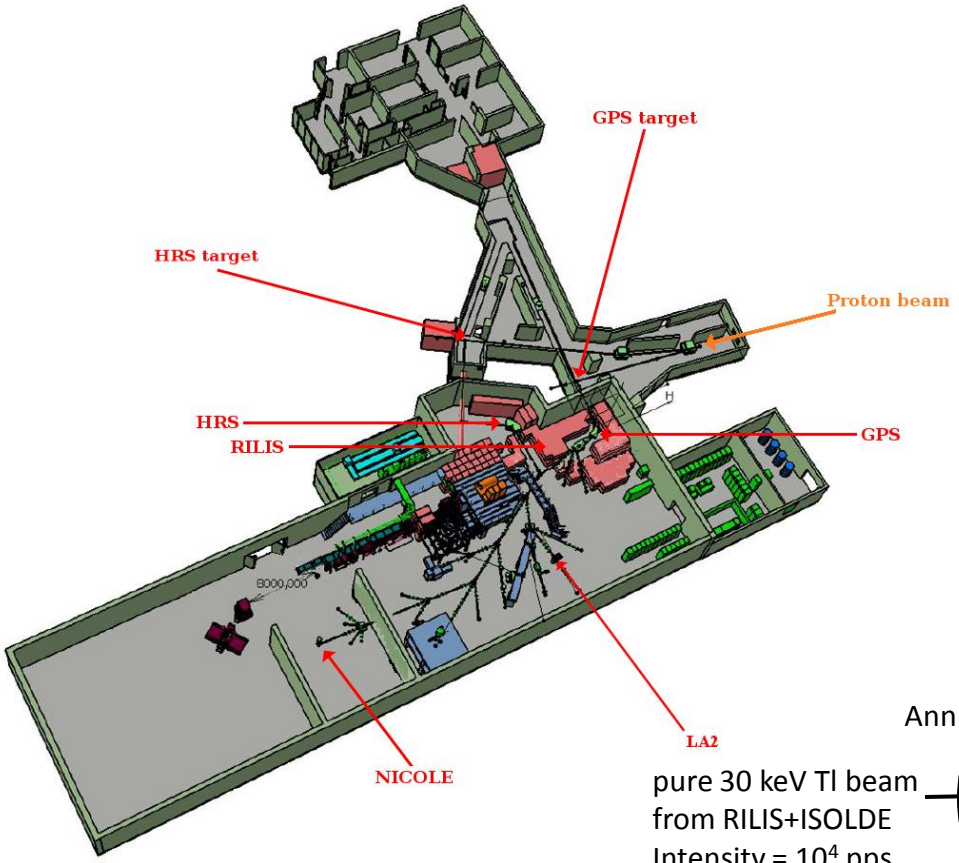


- In-source laser ionization and spectroscopy
  - $^{191\text{-}218}$Po
  - $^{182\text{-}190}$Pb
  - $^{180\text{-}182\text{-}184\text{-}186}$Tl
- Coulomb excitation
  - ^{200}Po → Nele Kesteloot: friday
  - ^{192}Pb
  - $^{182\text{-}184\text{-}186\text{-}188}$Hg → P. Butler: thursday
  - ^{224}Ra
- Life-time measurements on even Hg isotopes
  - $^{184\text{-}186\text{-}188}$Hg
- β^+/EC decay studies
  - decay into even-even $^{180\text{-}182\text{-}184}$Hg [1]
  - β-delayed fission

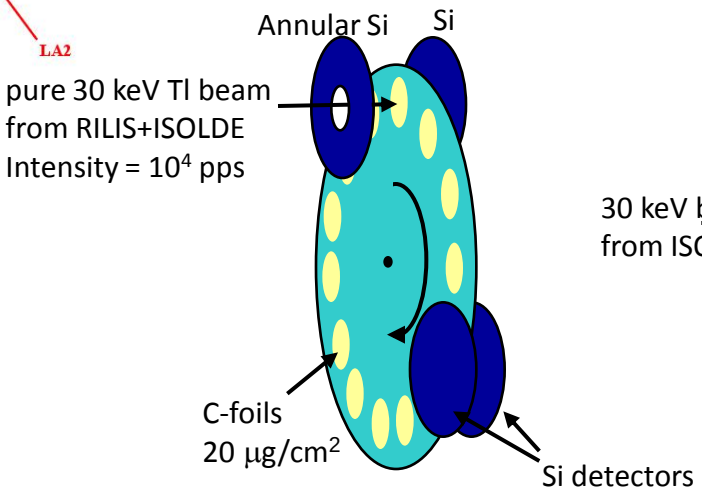
[1] ^{180}Hg, J.Elsevier et al., *Phys. Rev. C*, (2011)

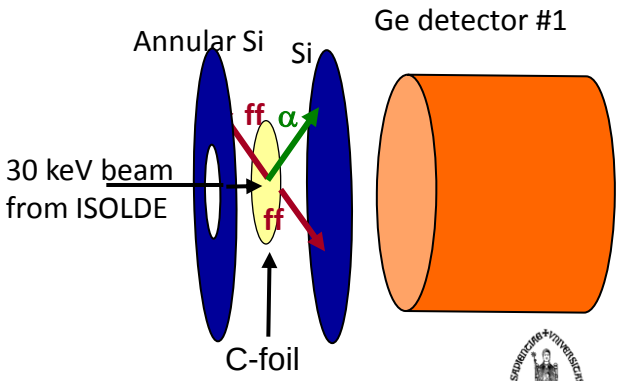
- α decay
  - ^{195}Po
  - $^{178\text{-}182}$Tl

β-spectroscopy: Experimental Setup

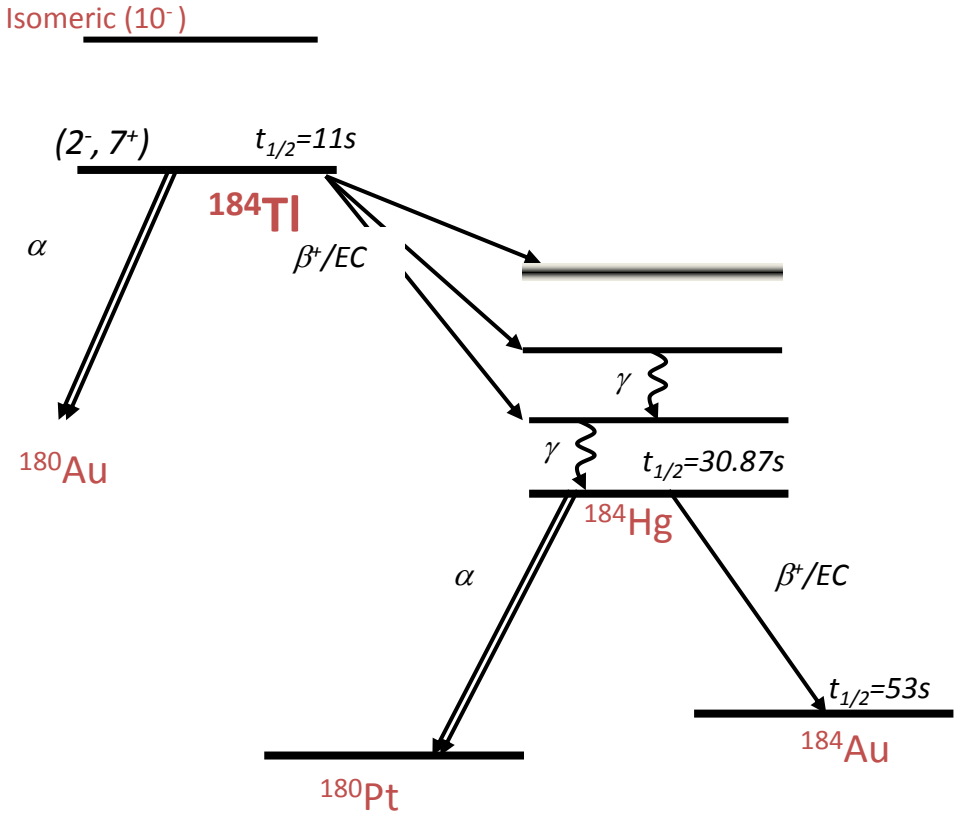


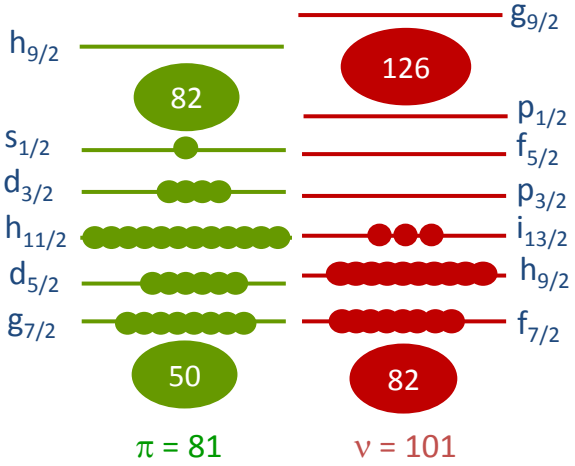
Windmill Chamber





The structure of ^{184}Tl





$\pi s_{1/2} \otimes \nu h_{9/2} = 4^-, 5^-$

$\pi s_{1/2} \otimes \nu i_{13/2} = 6^+, 7^+$

$\pi s_{1/2} \otimes \nu p_{3/2} = 1^-, 2^-$

} normal π states

OR

$\pi h_{9/2} \otimes \nu h_{9/2} = (0^+; 9^+)$

$\pi h_{9/2} \otimes \nu i_{13/2} = (2^-; 11^-)$

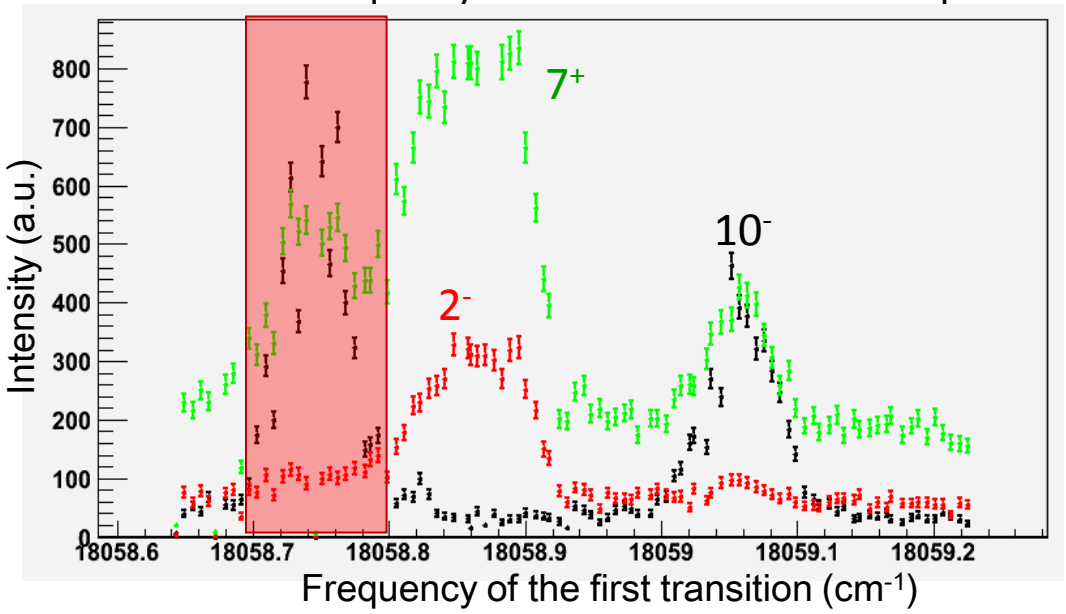
$\pi h_{9/2} \otimes \nu p_{3/2} = (3^+, 6^+)$

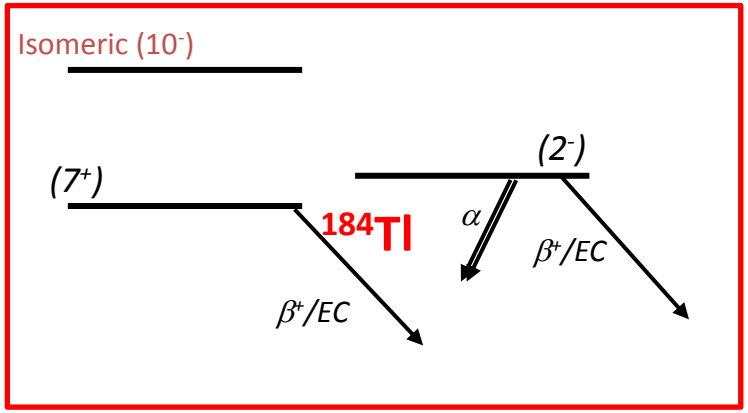
} intruder π states 1p-2h

Isomeric Beams @ ISOLDE

- technique based on in-source laser spectroscopy
(Ü. Köster et al., NIM B, 160, 528(2000); L. Weissman et al., PRC65, 024315(2000)).

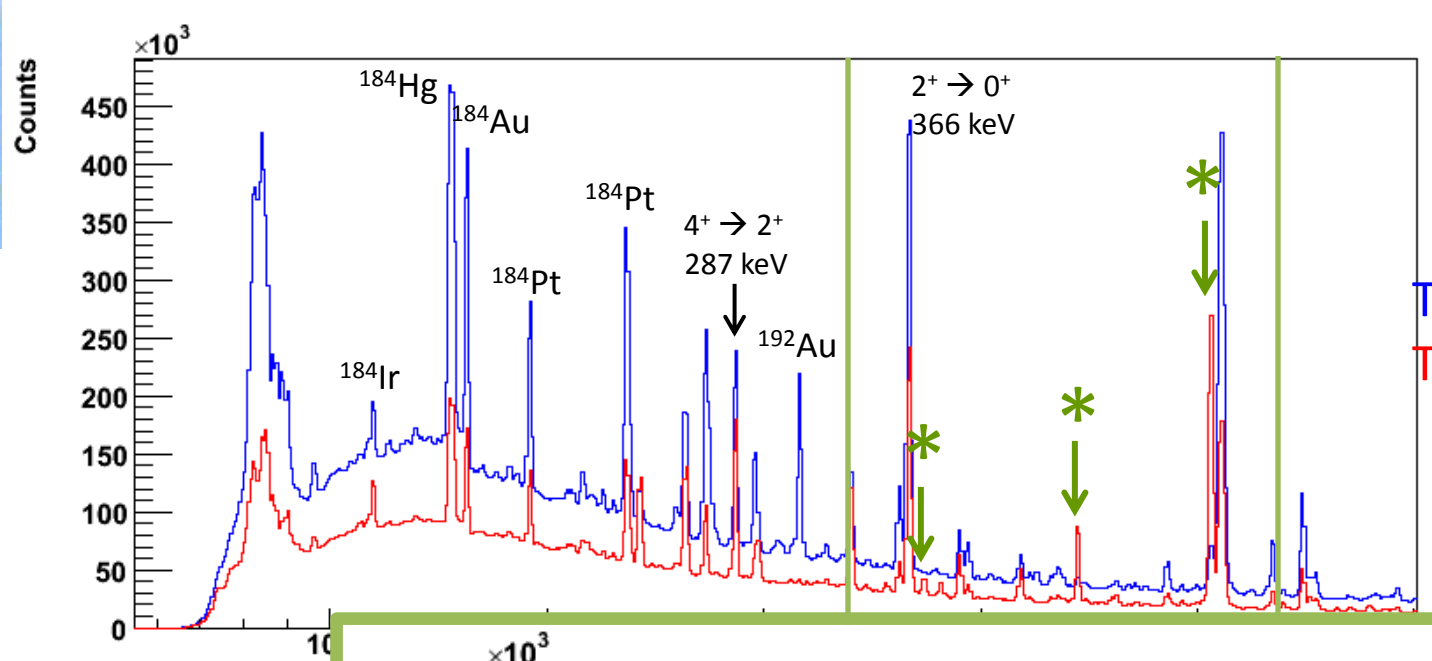
- set the laser frequency to select and maximize the production of the isomer of interest.





No laser: Tl is Surface Ionized
mixture of 2^-, 7^+, 10^-

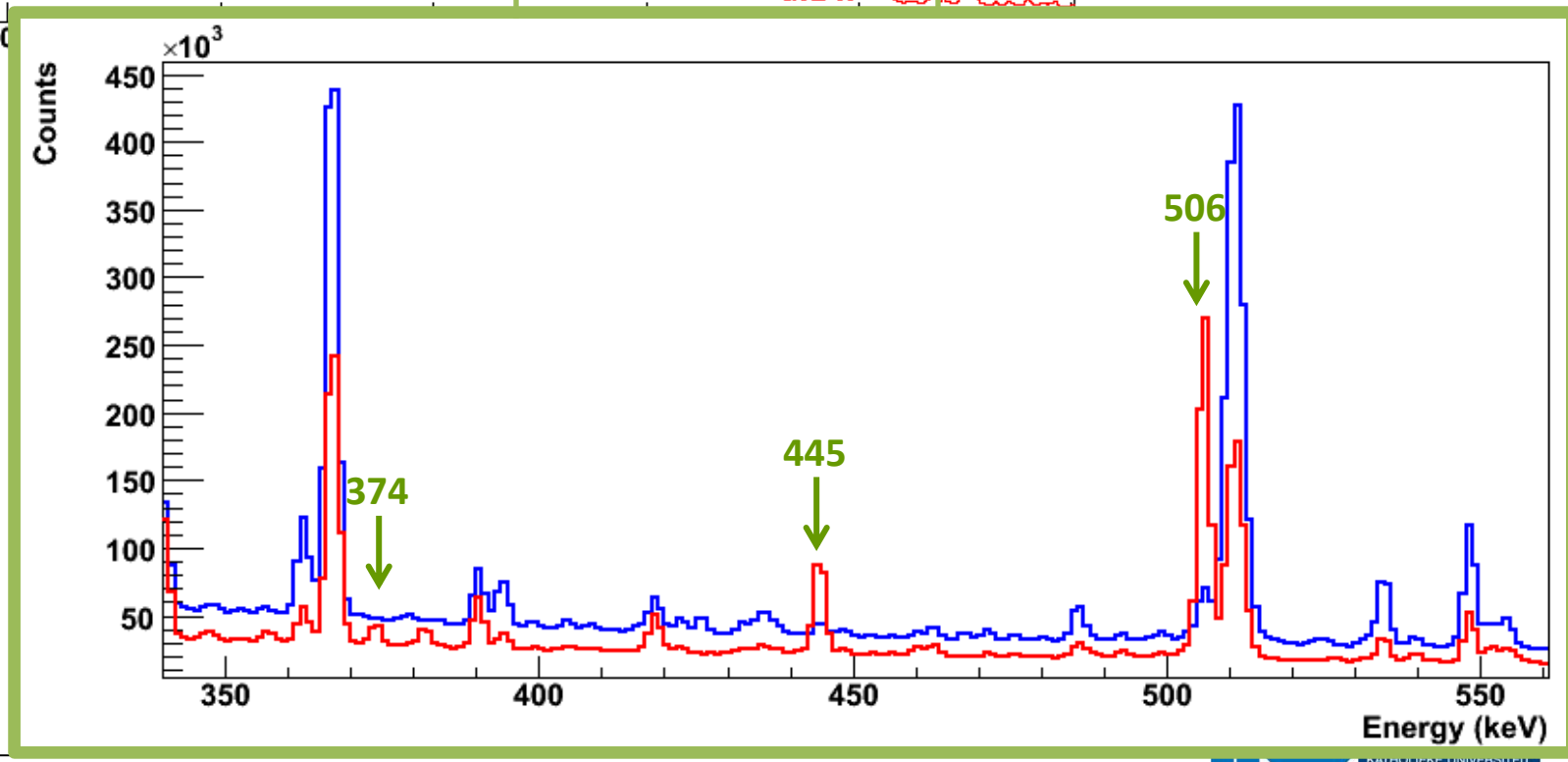
With laser: Laser set on 10^-
enhanced 10^- state



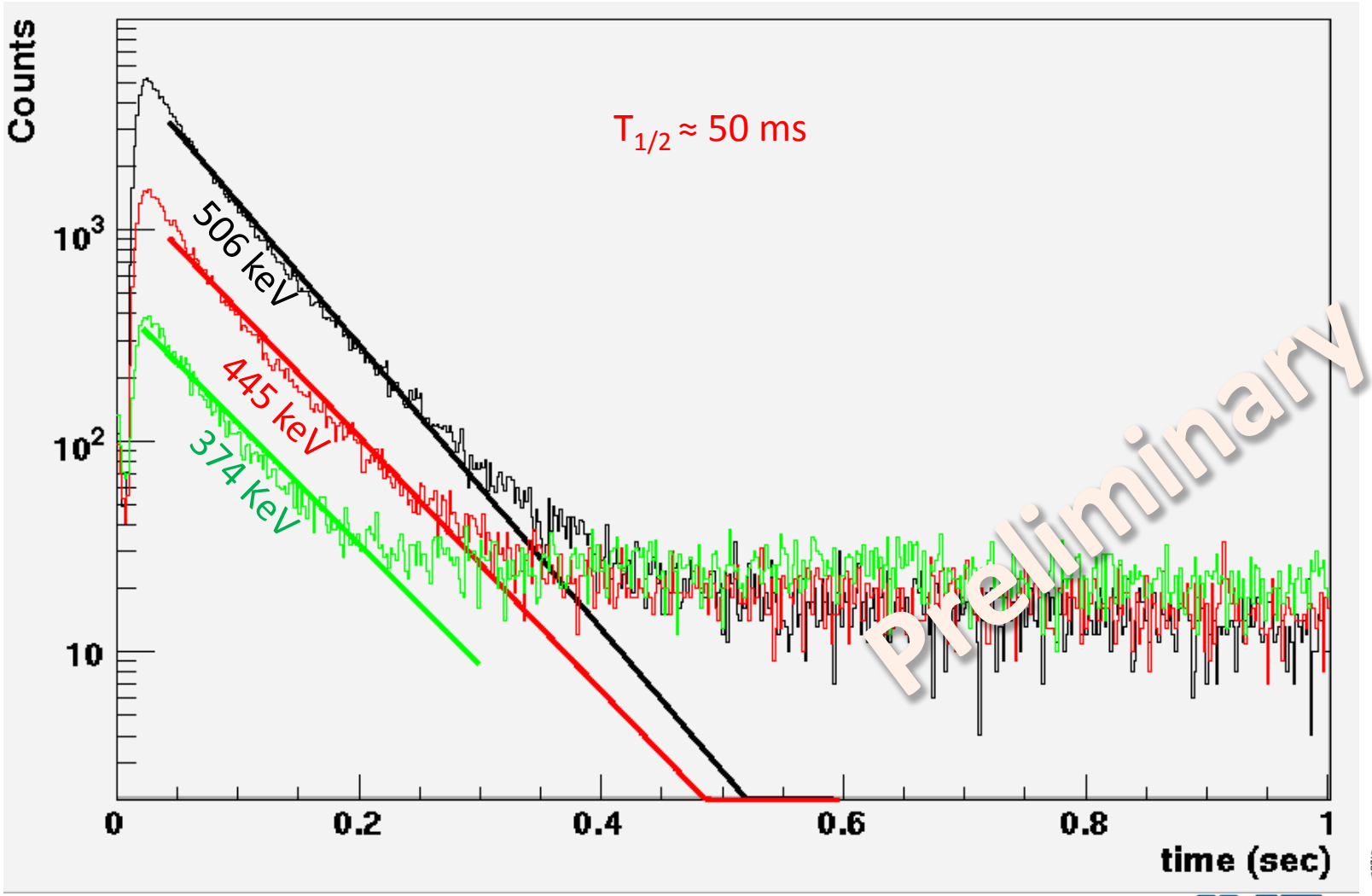
Tl - Surface ionized

Tl – laser ionized

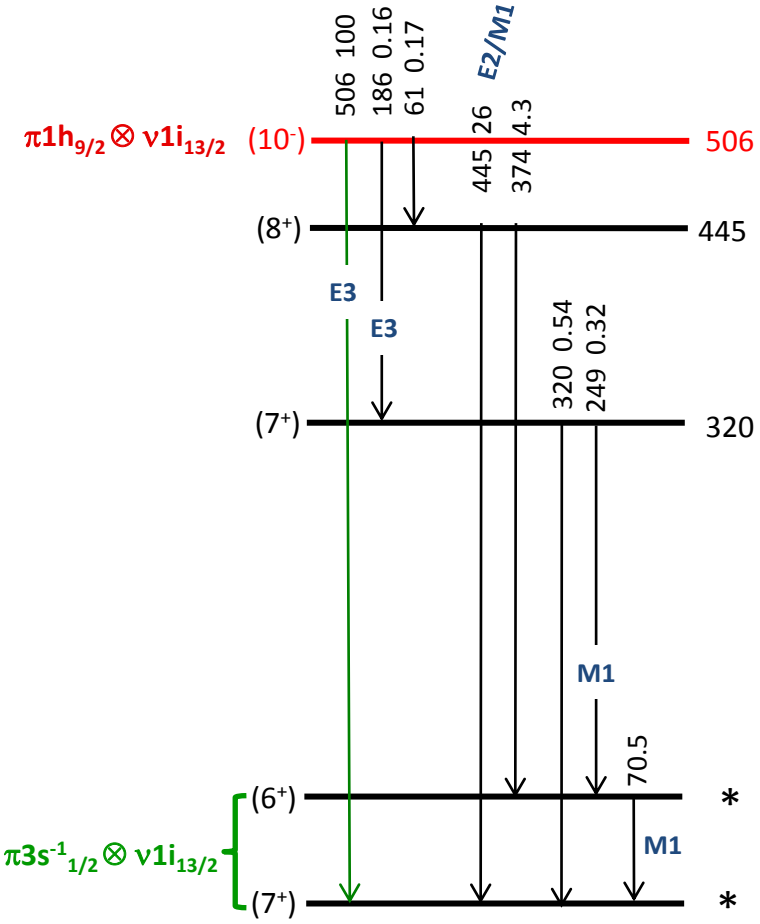
Single γ- spectrum

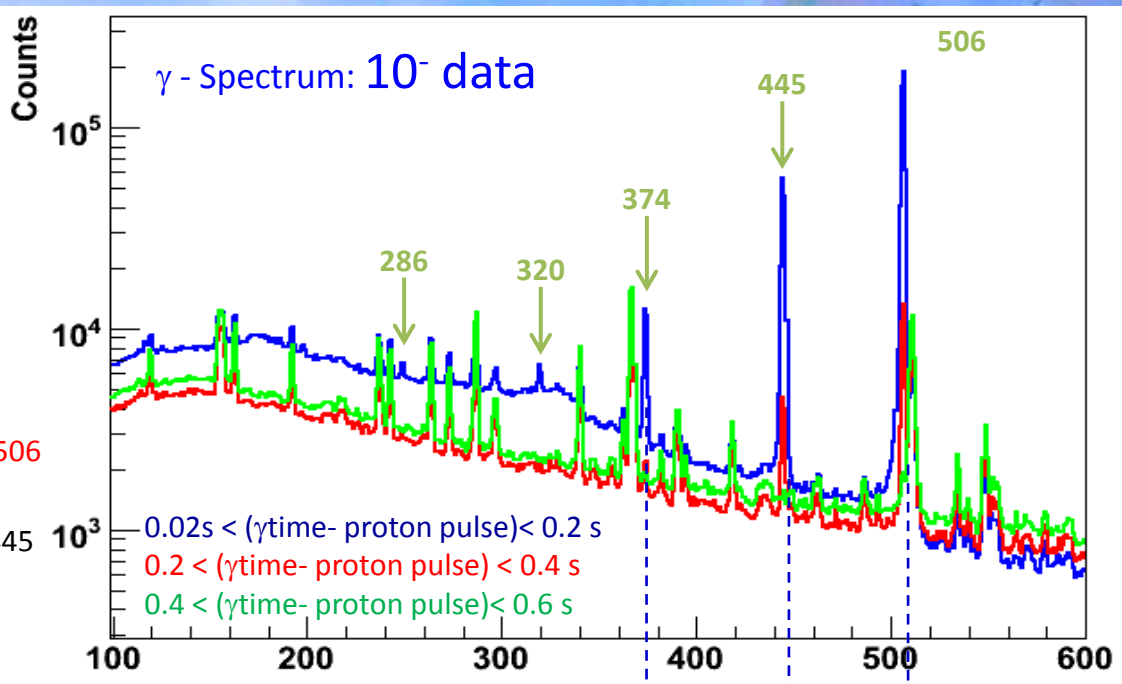


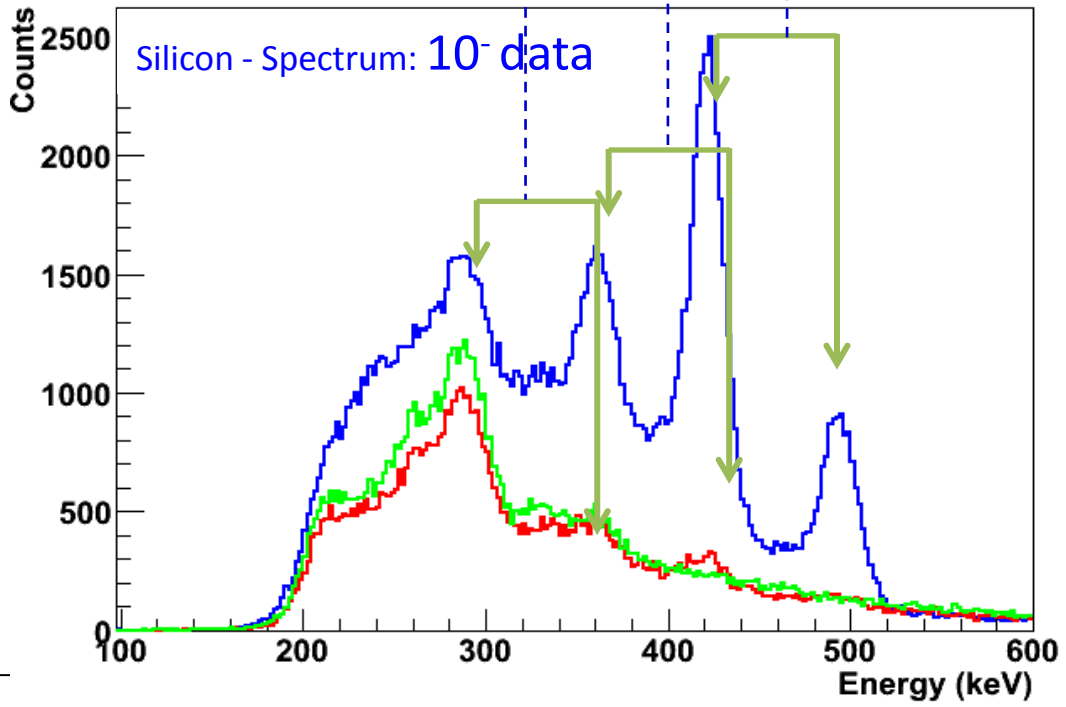
Half-life


Counts
10^3
10^2
10
0
0.2
0.4
0.6
0.8
1
time (sec)
$T_{1/2} \approx 50$ ms
506 keV
445 keV
374 keV
Preliminary

Isomeric decay of ^{184}Tl

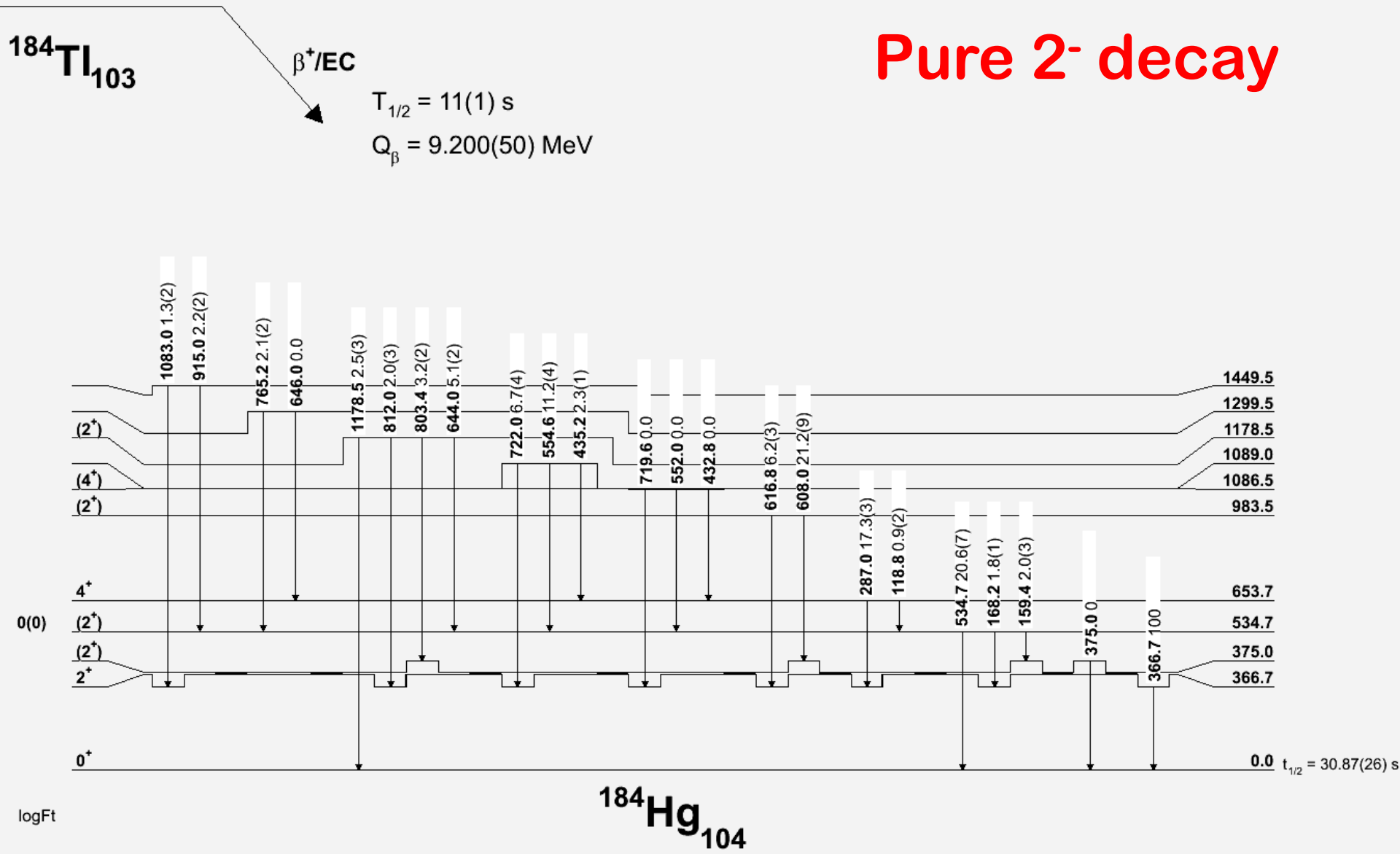






* A. Andreyev et al., Eur. Phys. J. A 18, 39–54 (2003)

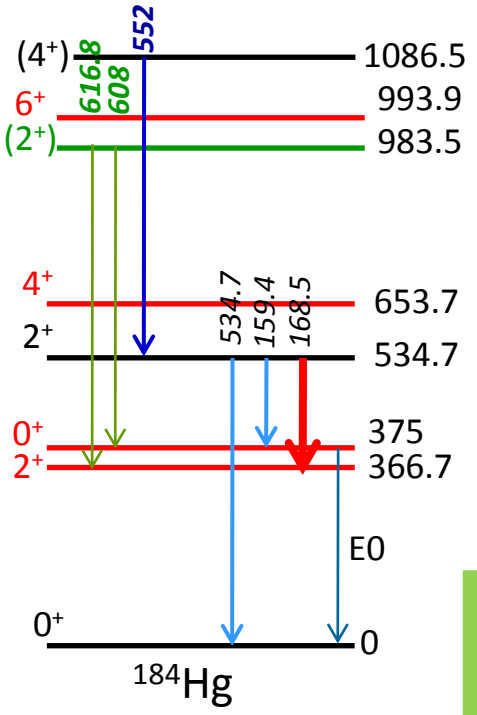
Result I: extensive decay scheme of ^{184}Hg



Result II: 0_2^+, 2_3^+ and level mixing

0_2^+ state: 375 keV

- identified by looking at Si-γ coincidences
- γ rays coincident with this Si energy: 608 keV



2_3^+ state: 983.5 keV

- based on unambiguous coincidence relations
- band-head of γ vibrational band on top of prolate band

$2_2^+ \rightarrow 2^+$ transition: 168.5 keV

- important E0 component (**ICC = $\frac{I_{CE}}{I_\gamma}$ = 23 (5)**)

Evidence for shape coexistence: transitions with E0 components are a model-independent signature of the mixing of configurations with different mean-square radii

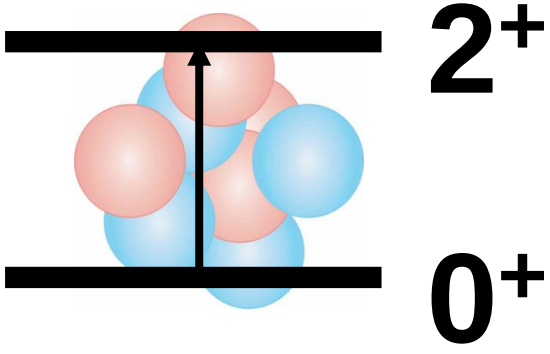
Result II: to be more quantitative → $\rho^2(E0)$

✓Complementary informations are needed …

$$ICC \rightarrow N_e(E0) + N_e(M1)^{?} + N_e(E2)^{?}$$

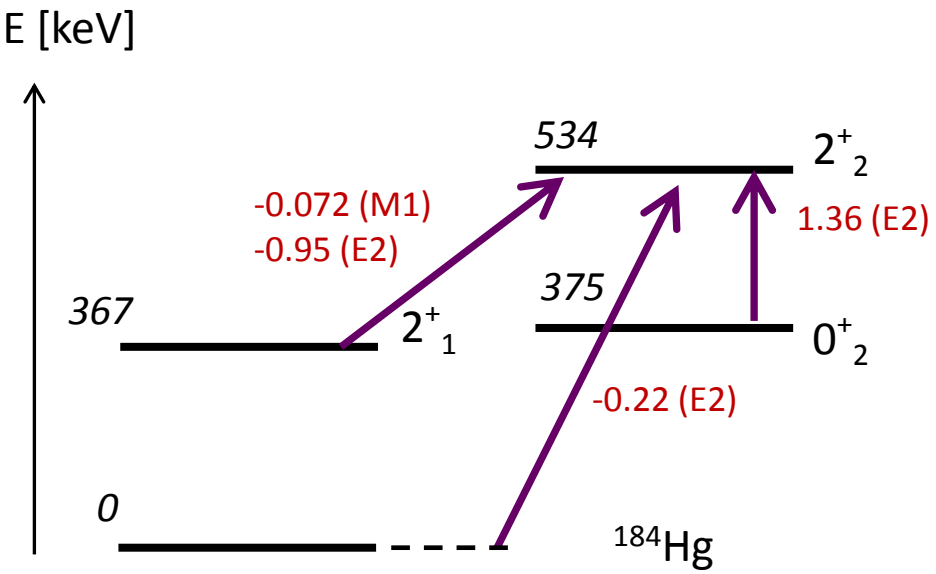
From Coulomb excitation of ^{184}Hg

(Nick Bree, PhD in KULeuven)



$$|\psi(0_1^+)\rangle = a\,|\varphi_{prol}\rangle + b\,|\varphi_{obl}\rangle$$

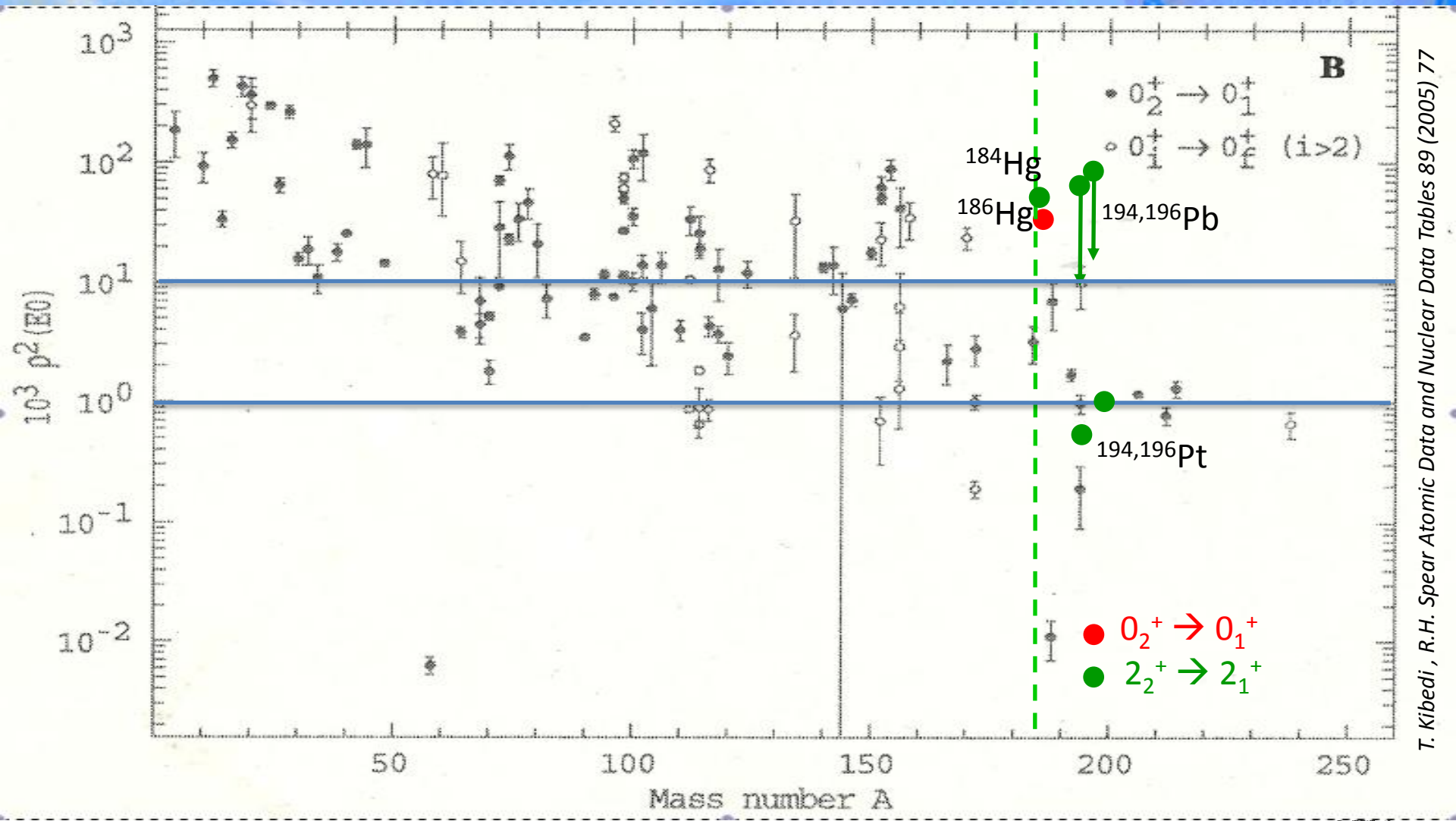
$$|\psi(0_2^+)\rangle = -b\,|\varphi_{prol}\rangle + a\,|\varphi_{obl}\rangle$$



Gosia2 calculations made by Kasia Wrzosek Lipska, KULeuven

We can get the strength of the E0 transition $\rho^2(E0) \times 10^3 \approx 41$ EXP

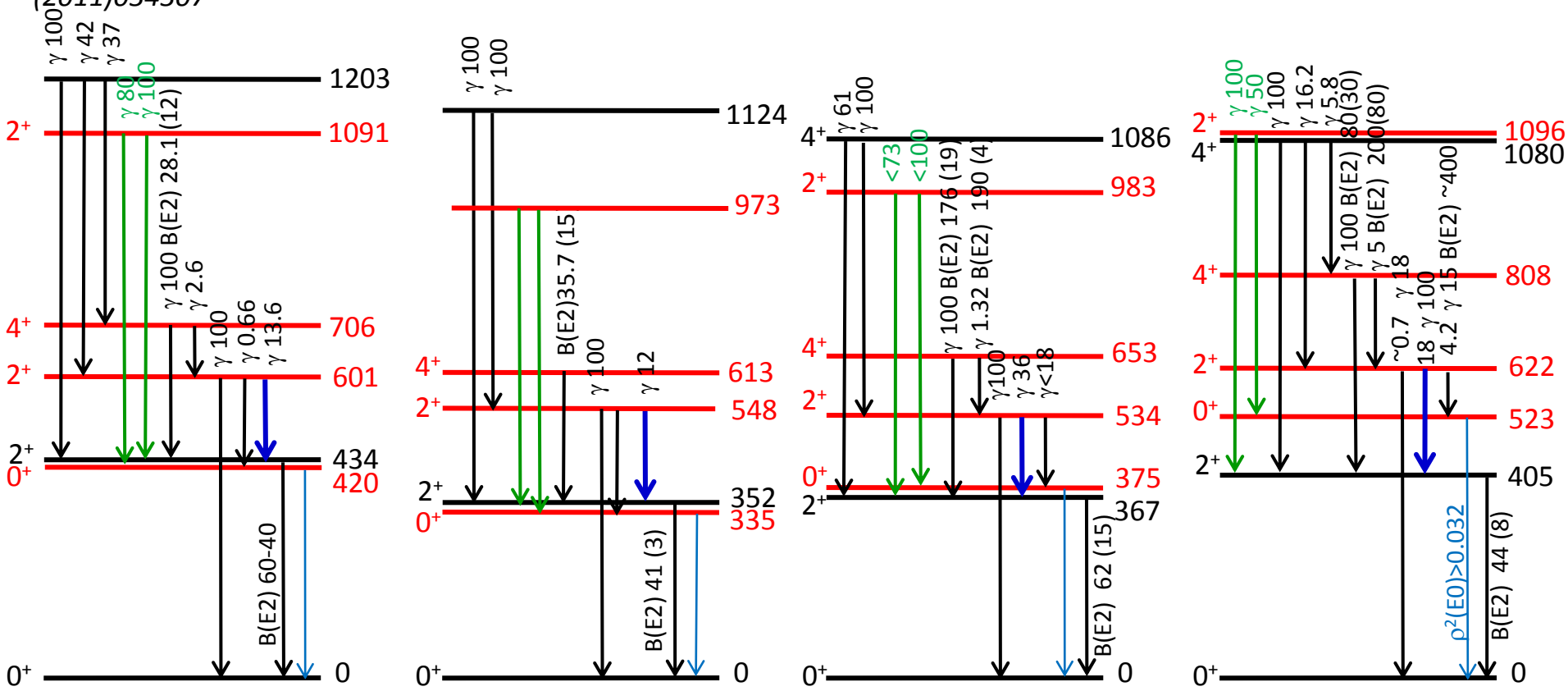
ρ^2(E0) systematics



Systematics of even Hg isotopes

J. *Elseviers et al. PRC84 (2011)034307*

NNDC.bnl.gov/ENSDF



$\alpha_{CE}(2^+_2 \rightarrow 2^+_1) = 3.5(4)$

$\alpha_{CE}(2^+_2 \rightarrow 2^+_1) = 4.2(8)$

$\alpha_{CE}(2^+_2 \rightarrow 2^+_1) = 23(5)$

Conclusions & Outlook

- β decay of ^{180,182,184}Tl populating levels in ^{180,182,184}Hg was studied as part of a systematic study

... What we have learned

- Many new low-lying energy states were observed
  0_2^+ which confirms minimum of prolate band occurs in ^{182}Hg

- $2^+ \rightarrow 2^+$ transitions observed with large E0 component
- the largest in ^{184}Hg.

... Next steps

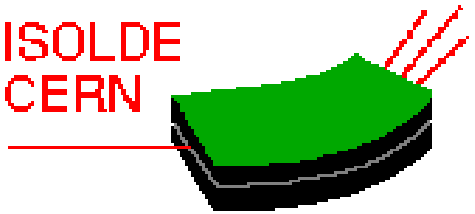
- More firm ground state spin assignment of Tl will follow from a hyperfine interaction study: Laser Spectroscopy
- Coulomb excitation of $^{182\text{-}188}$Hg will complement the known data with the direct measurement of the static quadrupole moment

Although we have already many different experimental probes at our disposition,
we still do not have a full picture of phenomena such as shape coexistence

But new possibilities arise:
- high resolution electron spectroscopy
- multiple Coulomb Excitation
- transfer reactions
- spins, moments and radii measurements in previously hardly accessible regions

Collaboration

- ✓ **IKS Leuven, Belgium -** I. Darby, J. Dirichen, J. Elseviers, N. Bree, M. Huyse, D. Pawels, D. Radulov, P. Van de Bergh, P. Van Duppen
- ✓ **University of West Scotland, UK –** A.N. Andreyev, V. Liberati, Joe
- ✓ **Comenius University, Bratislava, Slovakia -** M. Venhart, S. Antalic, M. Veselsky, Zdenka
- ✓ **University of Manchester, UK –** I. Tsekhanovich
- ✓ **University of Ioannina, Greece –** N. Patronis
- ✓ **Institute Laue Langevin, Grenoble, France -** U. Köster
- ✓ **CERN, Geneva, Switzerland –** T. E. Cocolios, V. Fedoseev, B. A. Marsh, M. Seliverstov, Anatoly, Pavel



and the ISOLDE collaboration

Acknowledgement: Marie Curie Intra-European Fellowship of the EC's FP7

Simple two-states model

Simple two-level models consist of two configurations corresponding to, in general, two shapes with different quadrupole equilibrium values in the appropriate deformation (β) space.

$$\rho^2(E0) = \alpha^2\ \beta^2\ \Delta\langle r^2\rangle^2\ Z^2/R^4$$

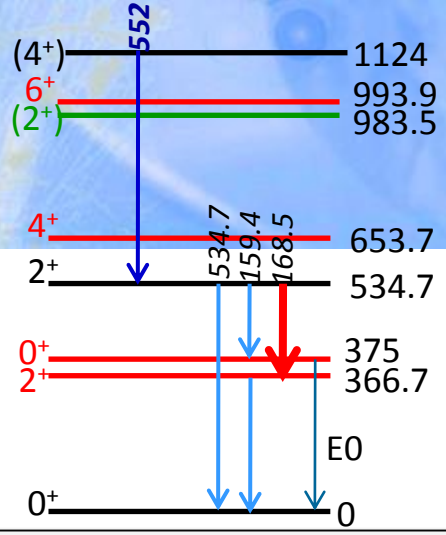
$\alpha^2 = ½$
$\beta^2 = ½$ 50:50 mixing

$\rho^2(E0) \times 10^3 \approx 223$ Expected

$\Delta\langle r^2\rangle = 0.55$ fm from Isomer Shift in odd-masses Hg

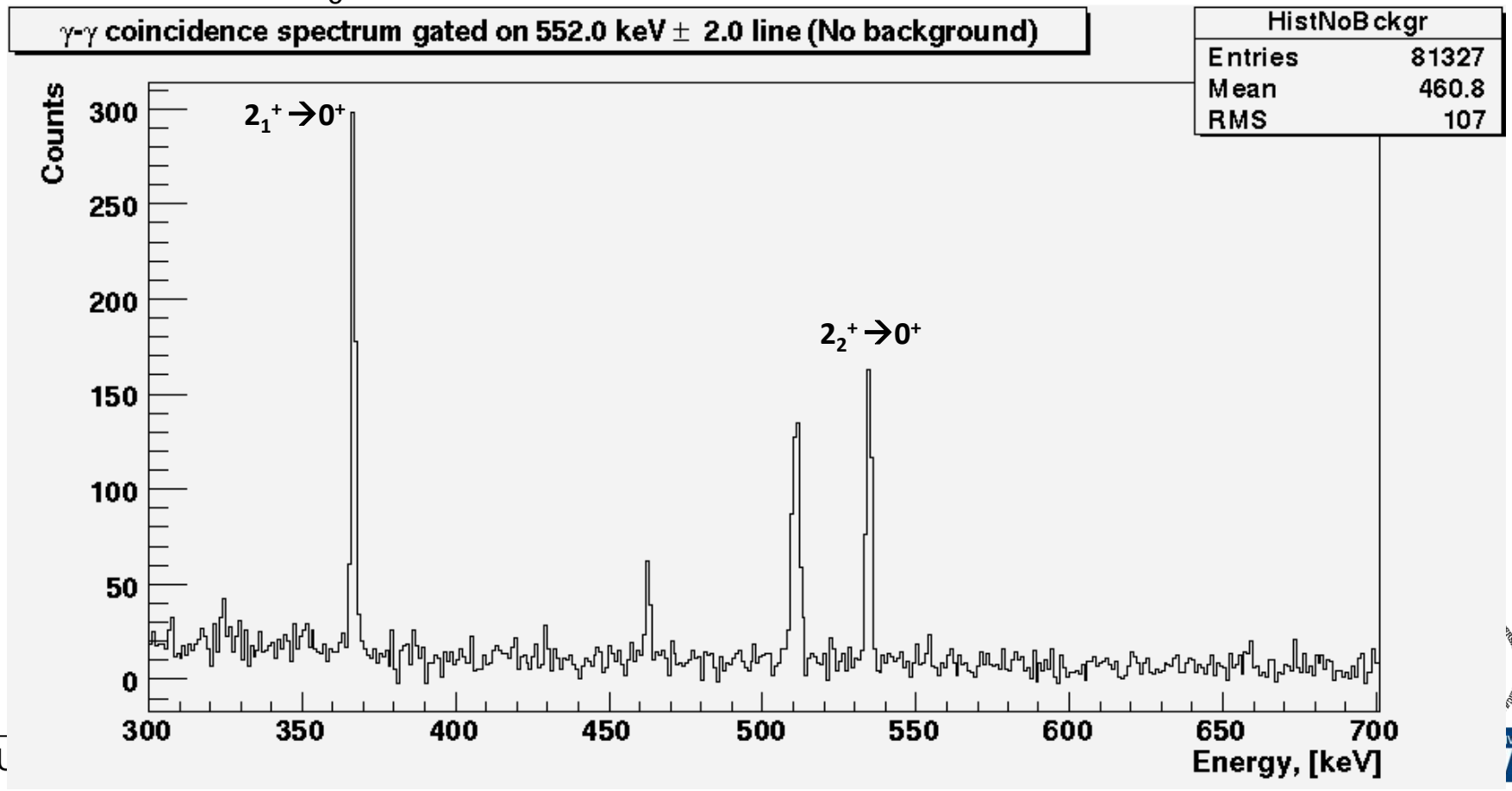
Estimate E0 component

$2_2^+ \rightarrow 2^+$ transition: 168.5 keV



How:

- gate on top of 2_2^+ → i.e. transition 552 keV;
- 168.5 keV not really seen in γγ coincidences with 552 keV;
- γ counts 168.5 estimated from comparison with I_γ (534.7)

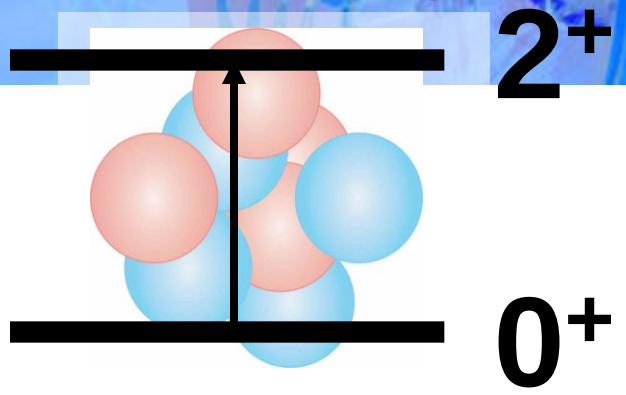


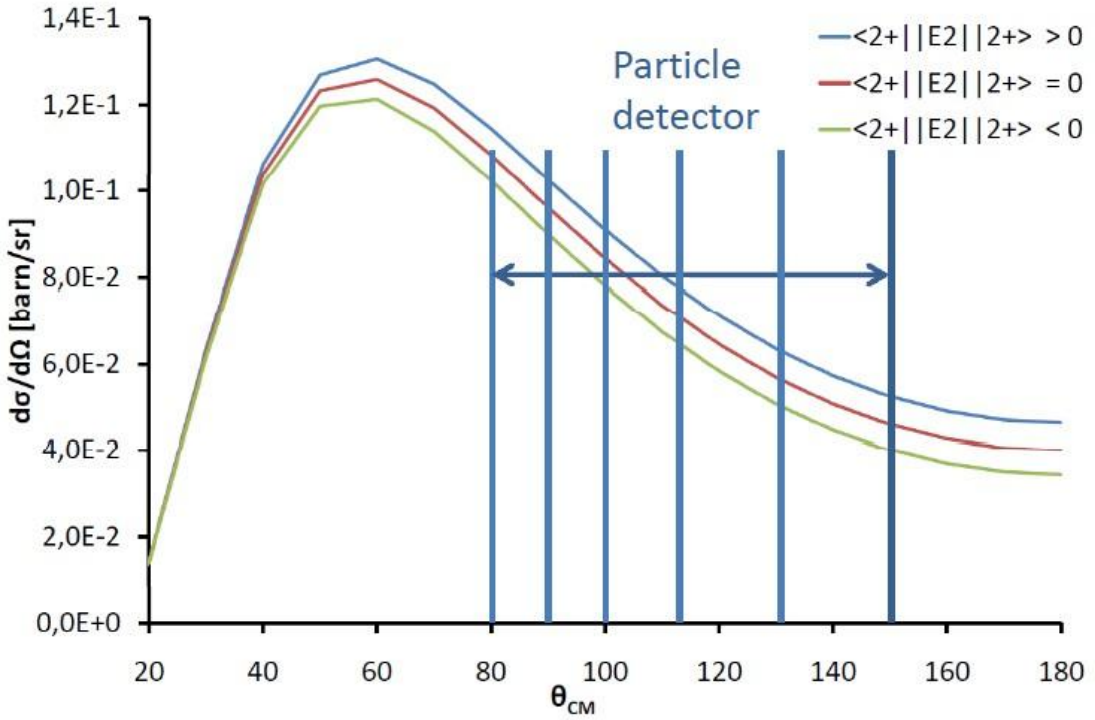
Coulomb Excitation of ^{182,184,186,188}Hg

Complement to each other!

- ✓energy of excited 0^+;
- ✓E0 strengths;
- ✓configuration mixing

→ Coulomb excitation to determine the nuclear shapes DIRECTLY



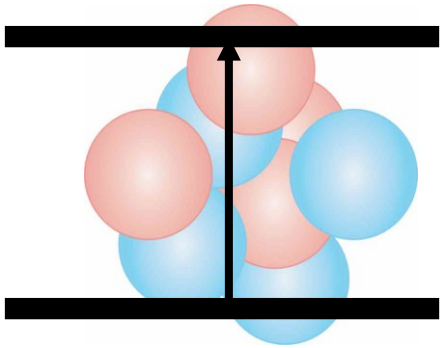


$$B(E2: 0^+ \rightarrow 2^+) \propto \left(\frac{d\sigma_{CE}}{d\Omega}\right)$$

The cross section for exciting the 2^+ state DOES NOT only depend on its reduced transition probability B(E2: 0^+ -> 2^+), but also on the diagonal matrix element $<2^+||M(E2)||2^+>$.

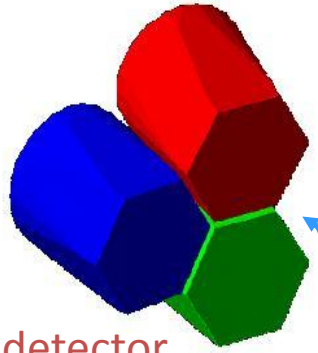
→ Obtain sensitivity on the diagonal matrix element of the first excited state by scanning the center of mass range!

Coulomb Excitation of ^{182,184,186,188}Hg



2^+

0^+



Miniball Ge detector

^{184}Hg

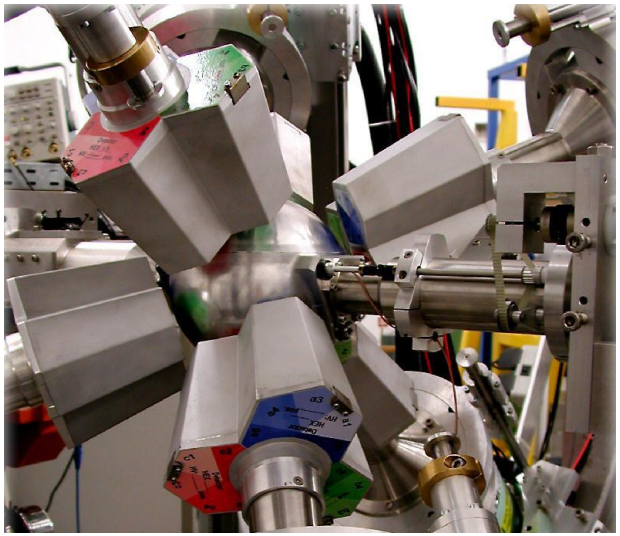
2,85 MeV/u

E_P

θ_P

target ^{120}Sn

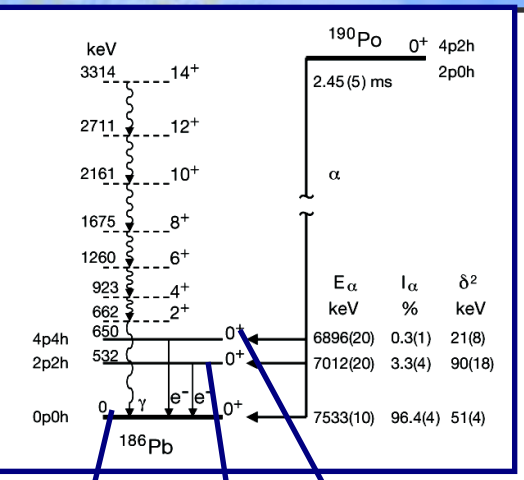
2.3 mg/cm^2

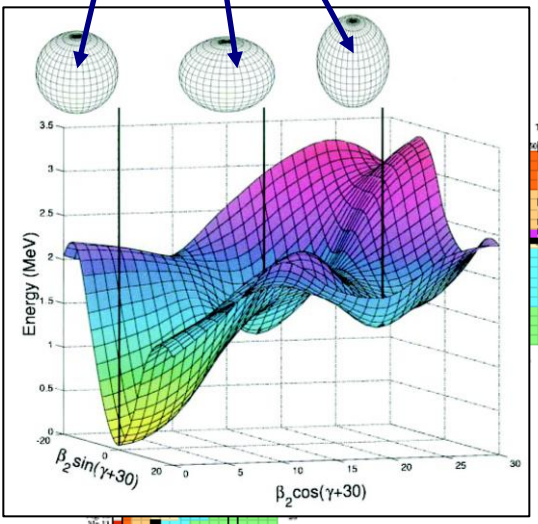


Double Sided Silicon Strip detector

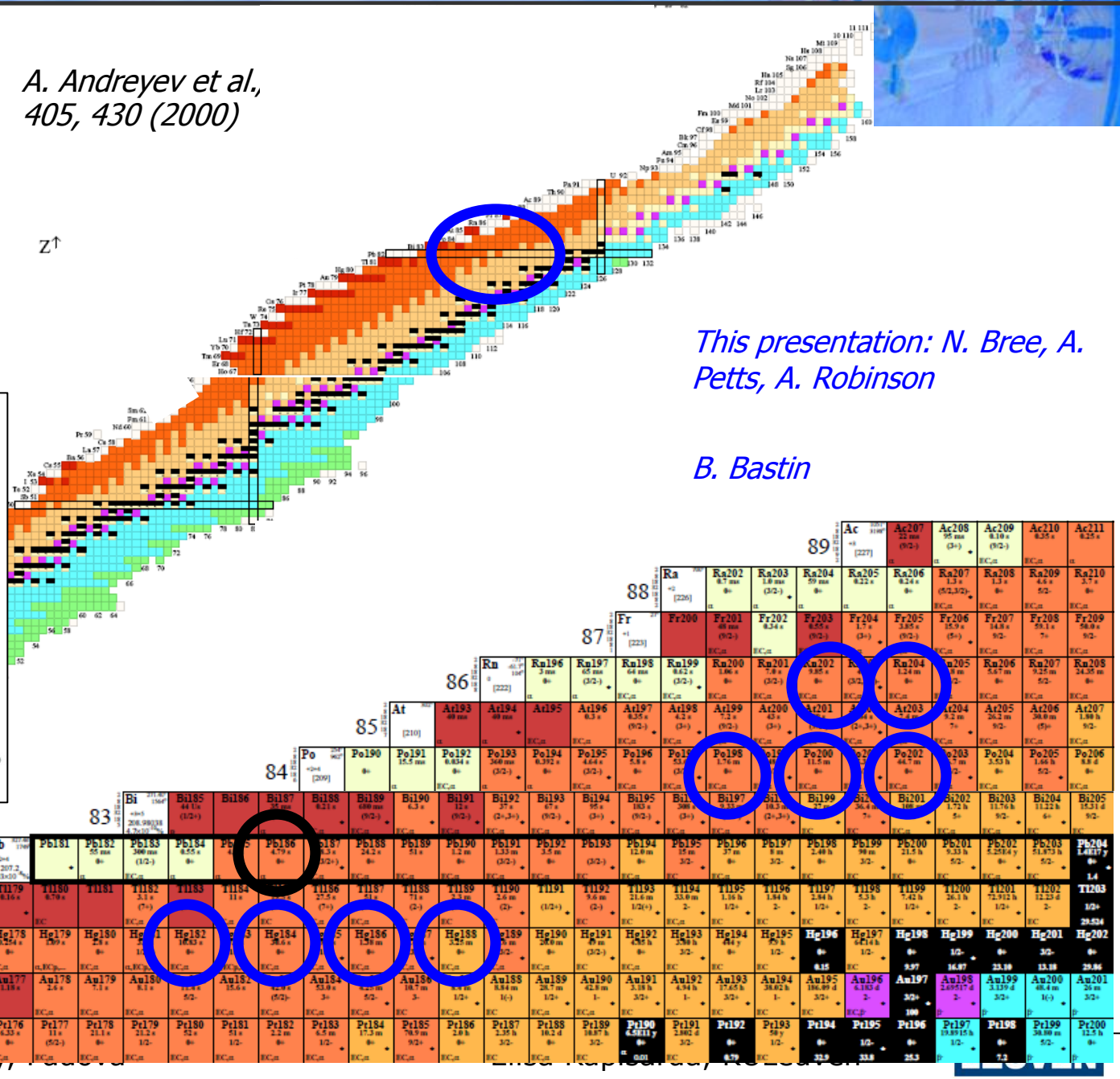
E_D

Physical Motivation





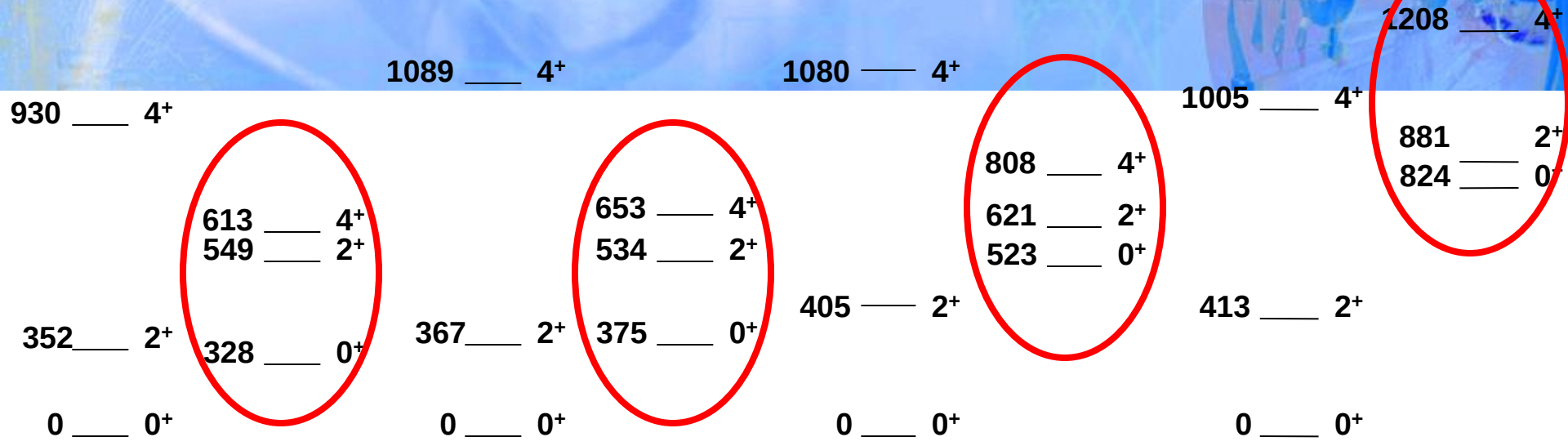
A. Andreyev et al., 405, 430 (2000)



This presentation: N. Bree, A. Petts, A. Robinson

B. Bastin

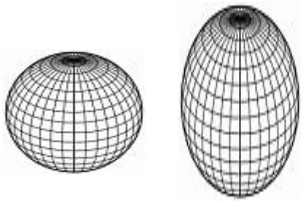
Physical Motivation



^{182}Hg ^{184}Hg ^{186}Hg ^{188}Hg

Ground state band: slightly oblate deformation $\beta_2 \approx -0.15$

Excited band: prolate deformation $\beta_2 \approx +0.25$



Coulomb excitation: the transitions observed reveal information on:

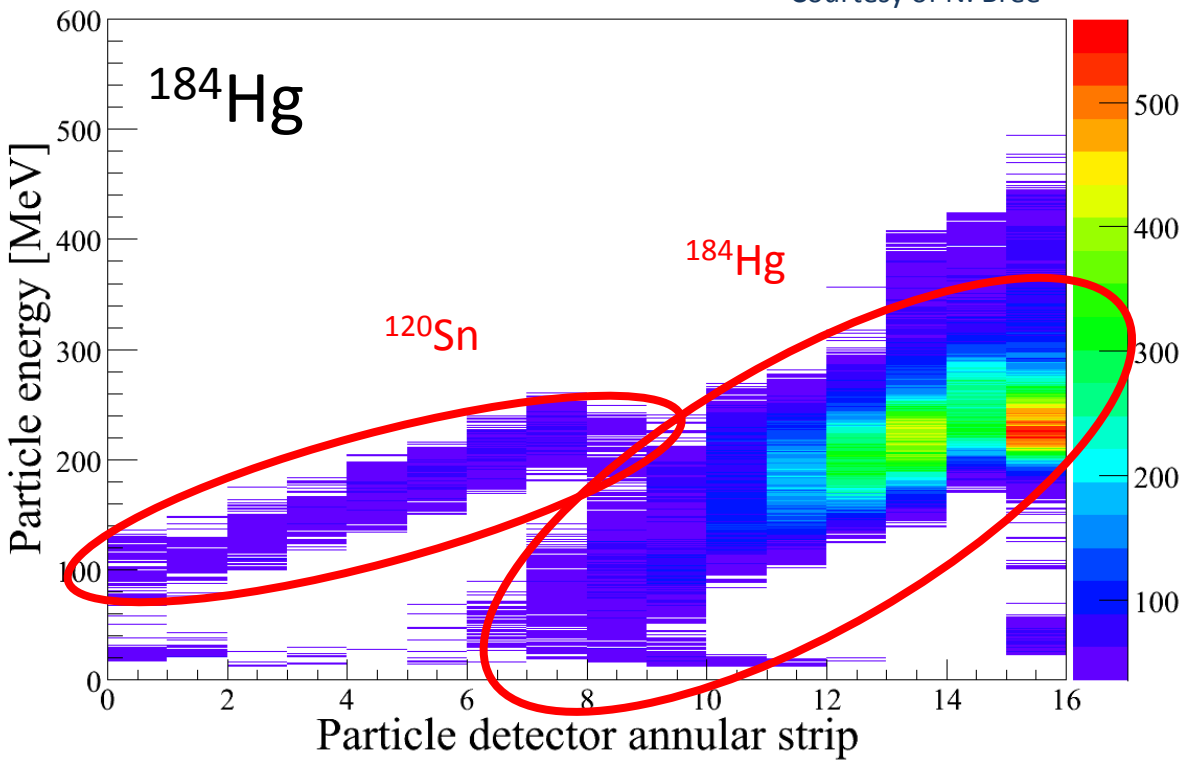
- Mixing between the different bands (transitional matrix elements)
- Information on the deformation (quadrupole moments)

B(E2) = 19500±4500 e^2fm^4

N. Rud et al, PRL 31, 1421, 1973

+ life time measurements

Courtesy of N. Bree

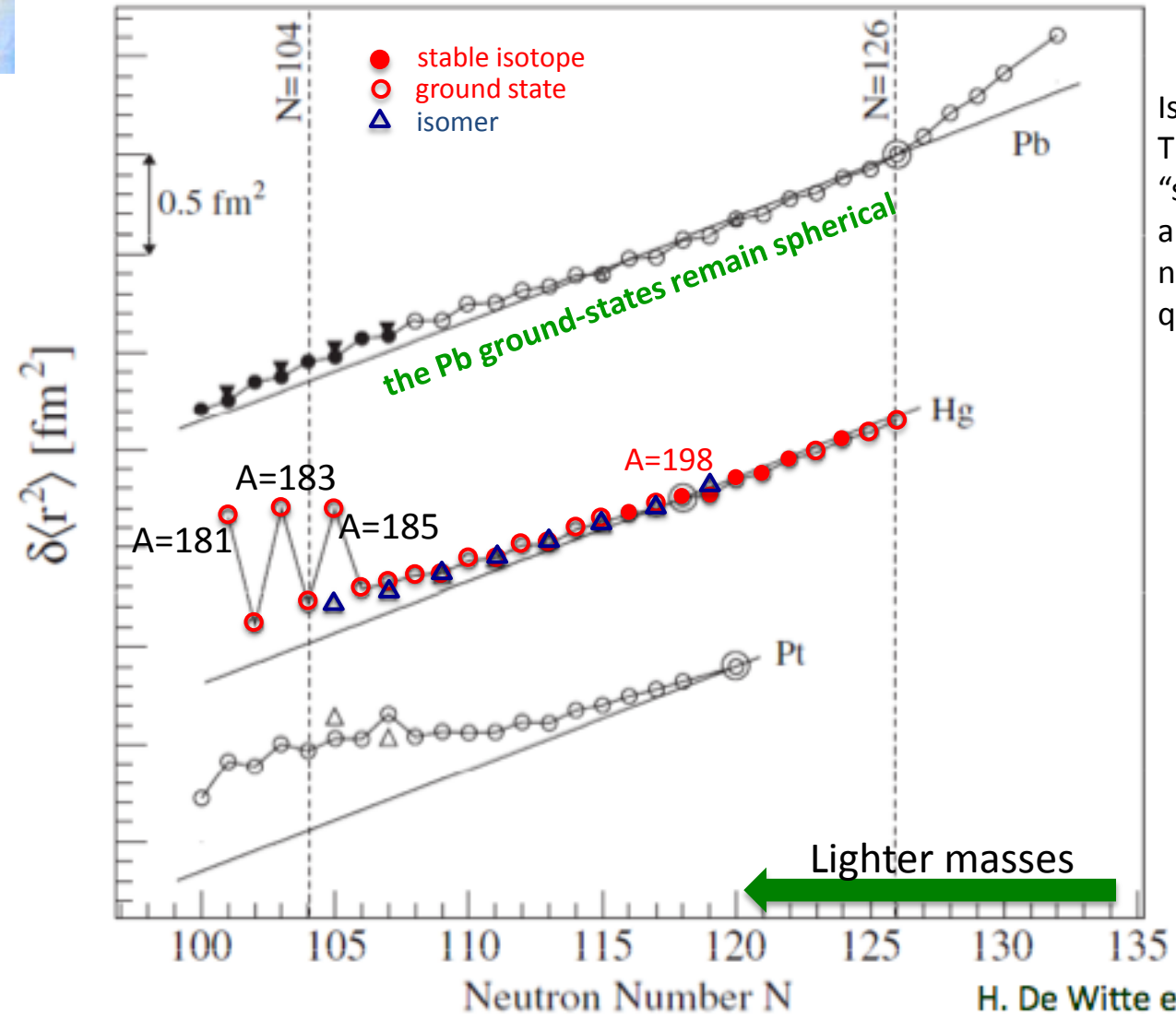


The detected γ yields of the photo peaks can be used to extract:

- transitional matrix elements (B(E2) values)
- diagonal matrix elements (quadrupole moments)

This is done by the program GOSIA by fitting the matrix elements to produce the obtained γ yields by a χ^2 minimization.
(T. Czosnyka et al, *GOSIA2*)

Normalized mean-square radii



H. De Witte et al., PRL98(2007) 112502

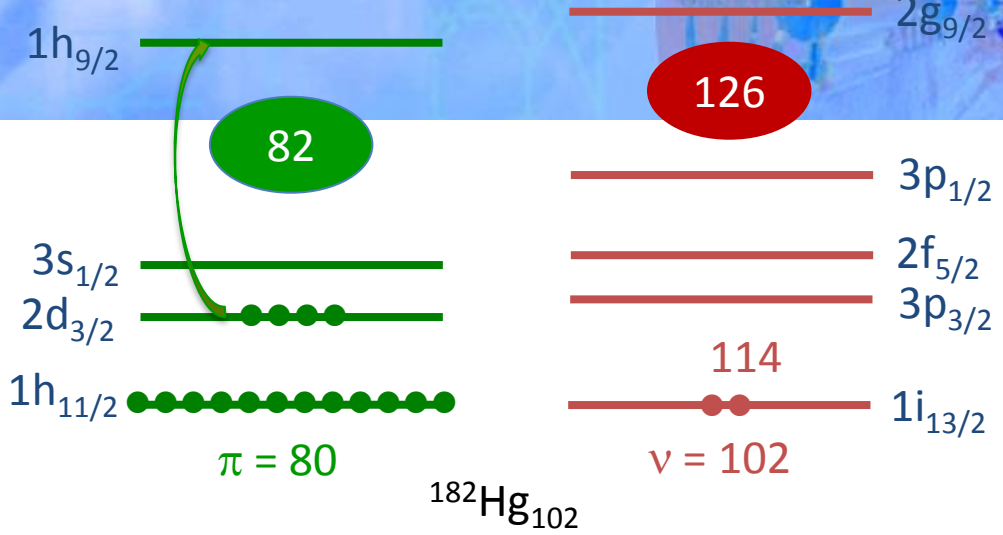
Spectroscopic fingerprint

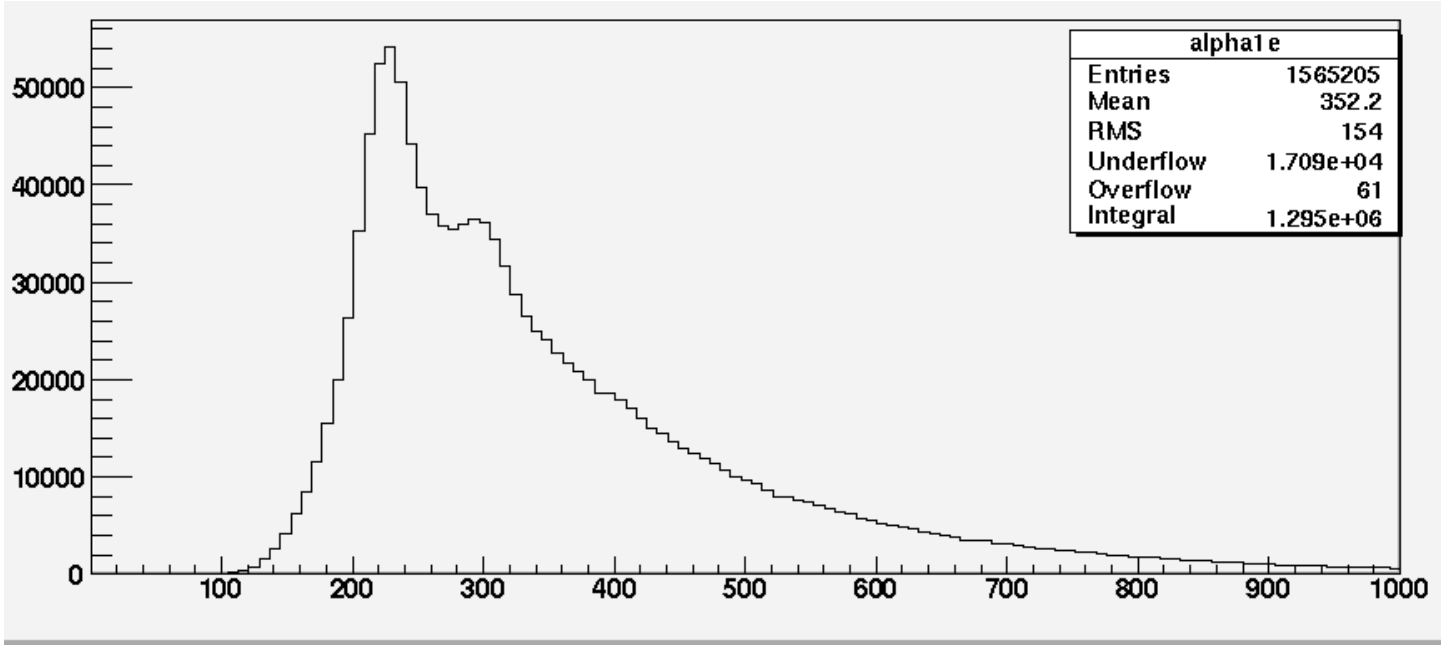
Isotope shift systematics:
The large increases and "staggering" in the N ≈ 104 region are the result of states in these nuclei with very different quadrupole deformations

Descrizione della figura:
DA FARE
Non mi è chiara per niente

The relative $\delta\langle r^2\rangle^{N,124}$ are normalized within each isotope to $\delta\langle r^2\rangle^{122,124}$

Since the B(E2) value is known, the sign and magnitude of the quadrupole moment of the 2^+ state can be measured by calculating the excitation cross section out of the intensity of the detected γ photo peak of the $2^+ \rightarrow 0^+$ transition.

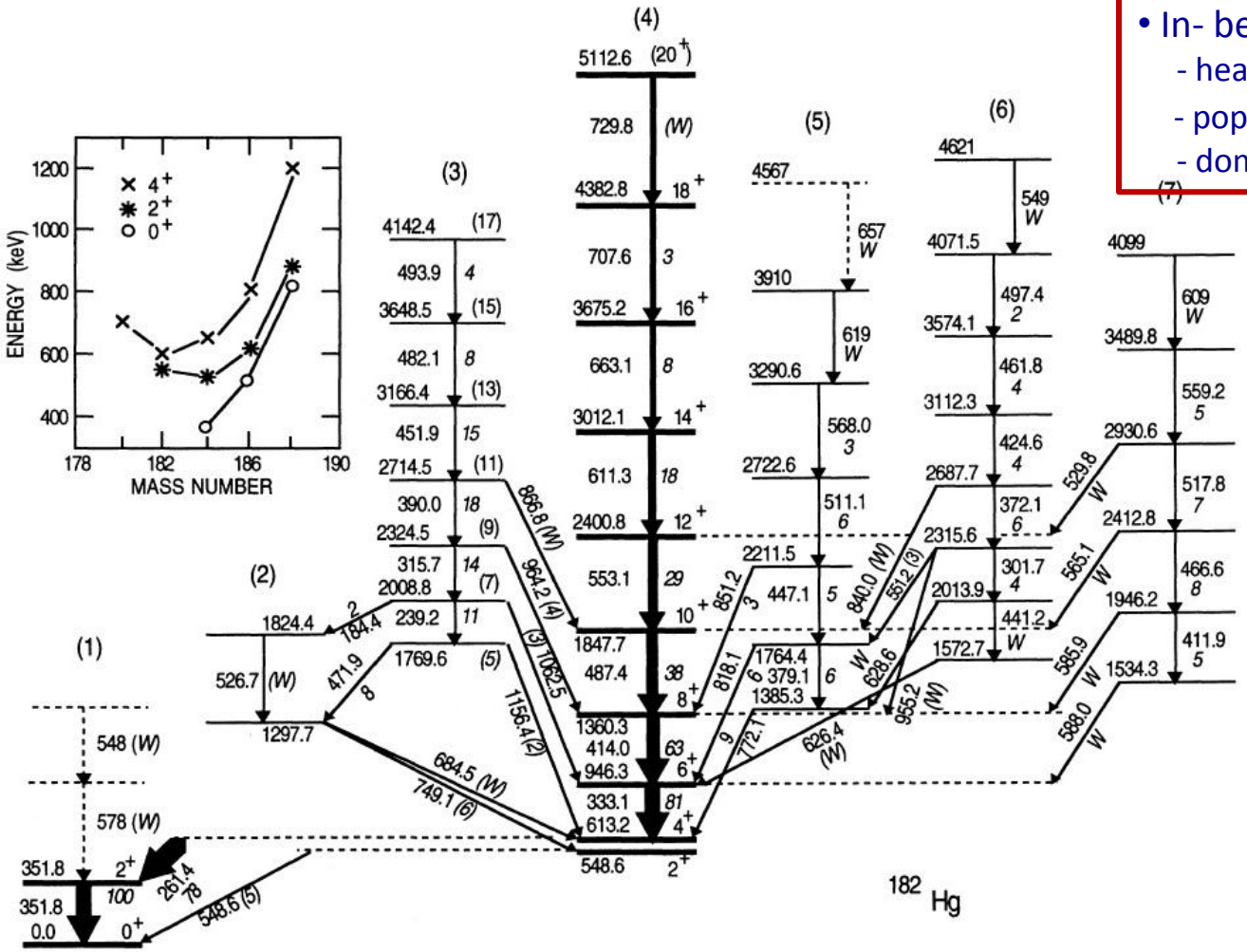


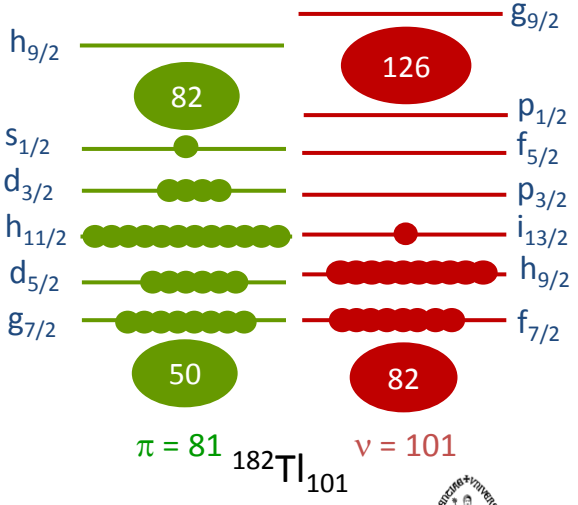


^{182}Hg

In beam γ-ray spectroscopy [1] :

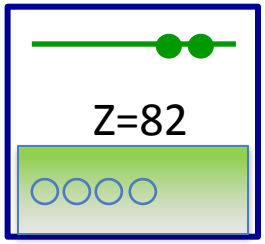
- In- beam γ-spectroscopy
  - heavy ions fusion-evaporation reaction
  - population of high spin states up to I=20
  - dominantly yrast states



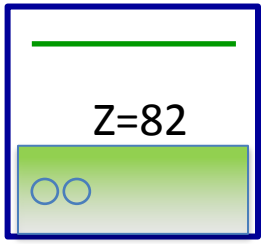


[1] K.S. Bindra et al., *Phys. Rev. C*, 51 (1995) 401

Intruders ....



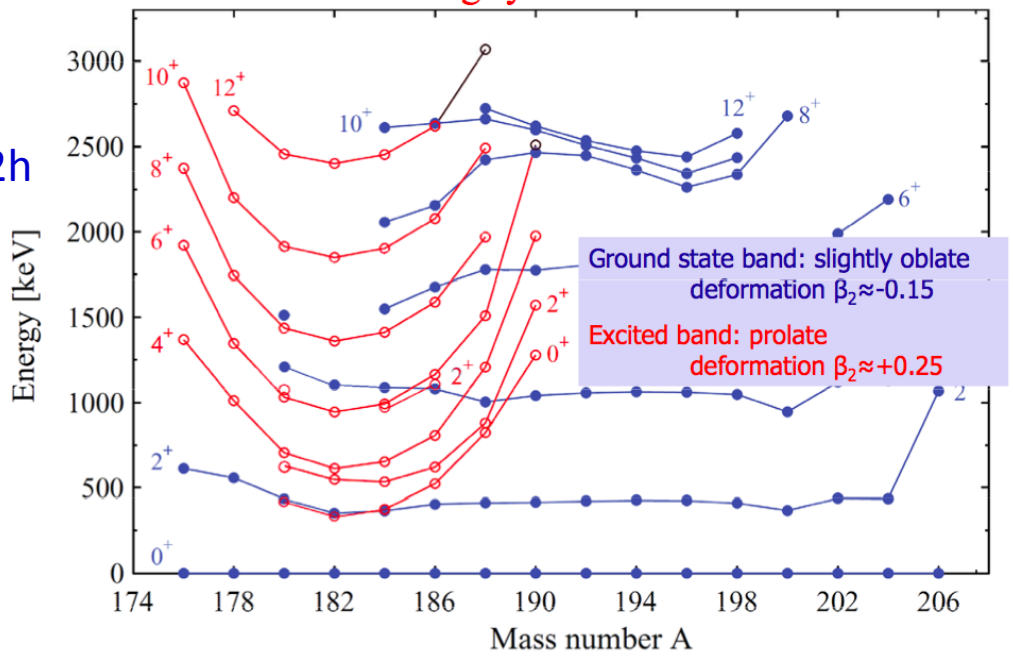
Excited band: 2p-4h
unperturbed $|\varphi_{prol}\rangle$



Ground state band: 0p-2h
unperturbed $|\varphi_{obl}\rangle$

intruder states:
proton excitations across the Z = 82 closed shell

Even Hg systematics

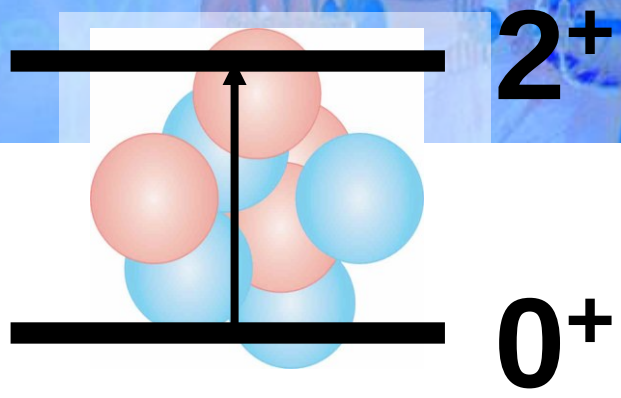


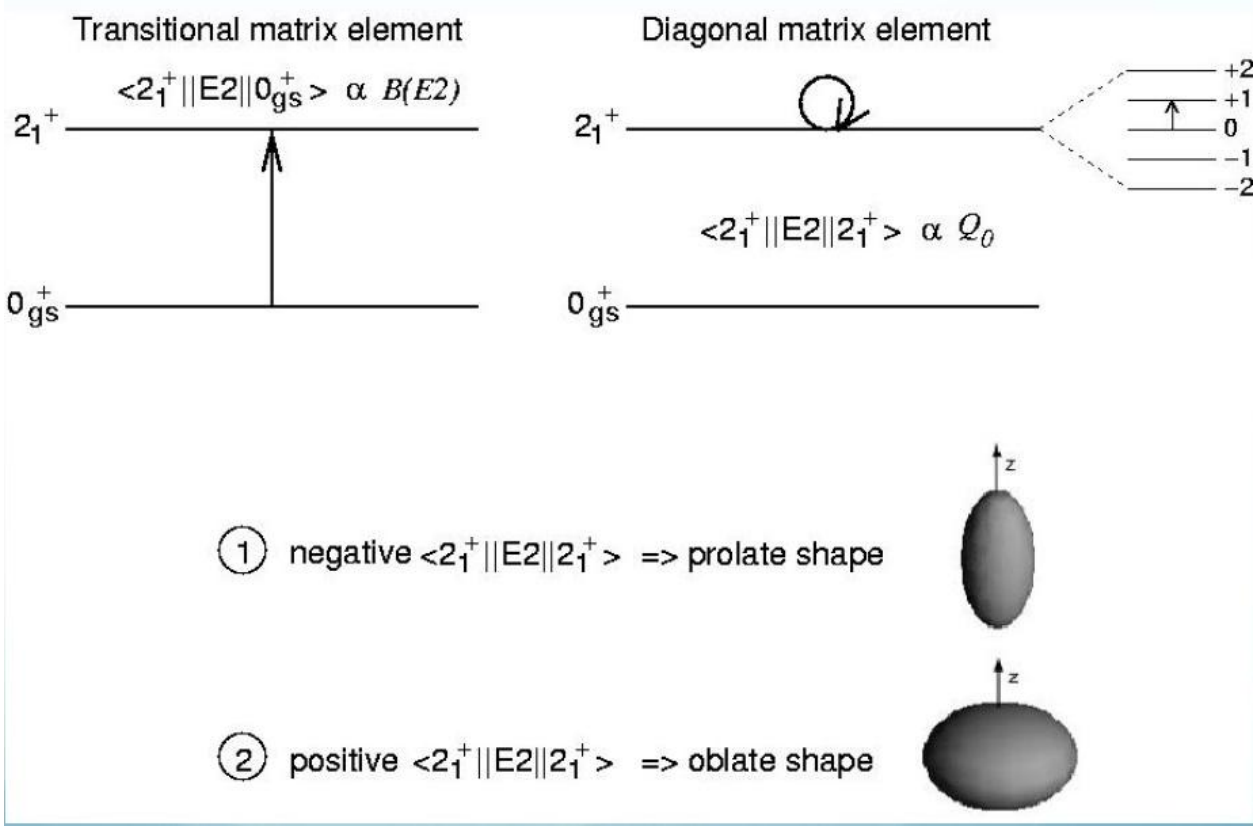
Configuration mixing

$$|\psi(0_1^+)\rangle = a\,|\varphi_{prol}\rangle + b\,|\varphi_{obl}\rangle$$

$$|\psi(0_2^+)\rangle = -b\,|\varphi_{prol}\rangle + a\,|\varphi_{obl}\rangle$$

Reorientation in Coulomb Excitation

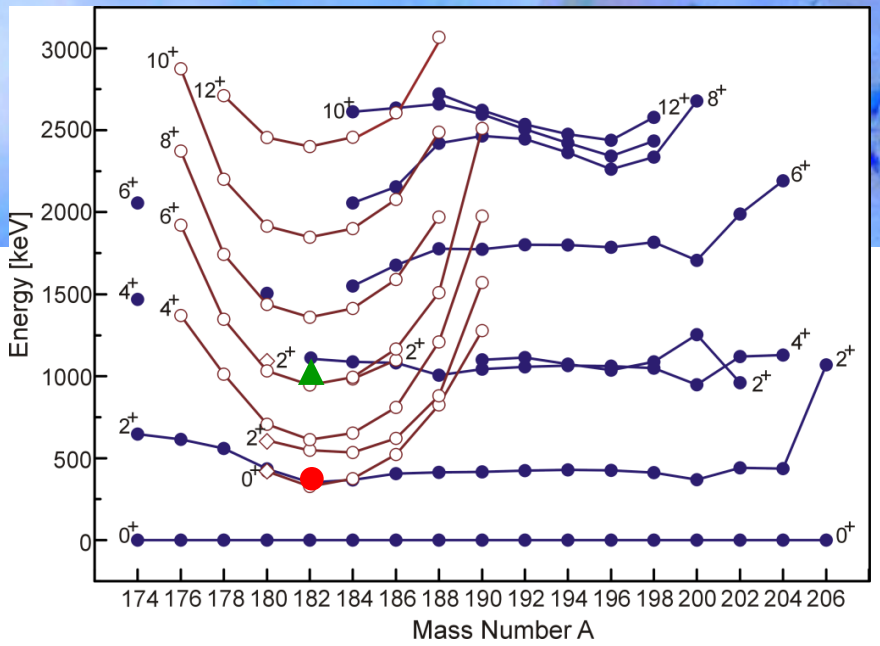


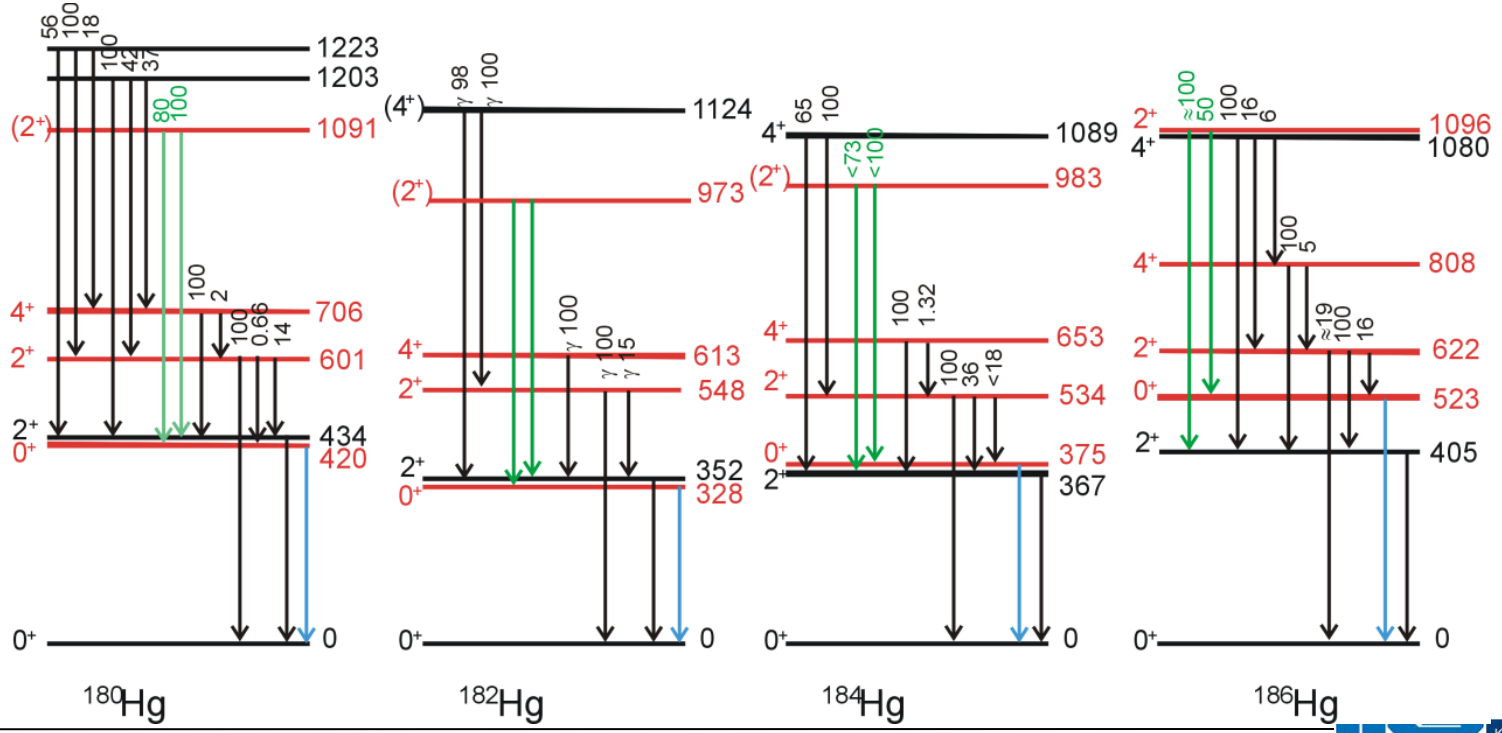


- ✓ Coulomb excitation excites low-lying collective bands with cross sections that are a direct measurement of the Eλ matrix elements involved in the excitation.
- ✓ Collectivity and deformation can be inferred.
- ✓ Reorientation effects can provide the sign of Q

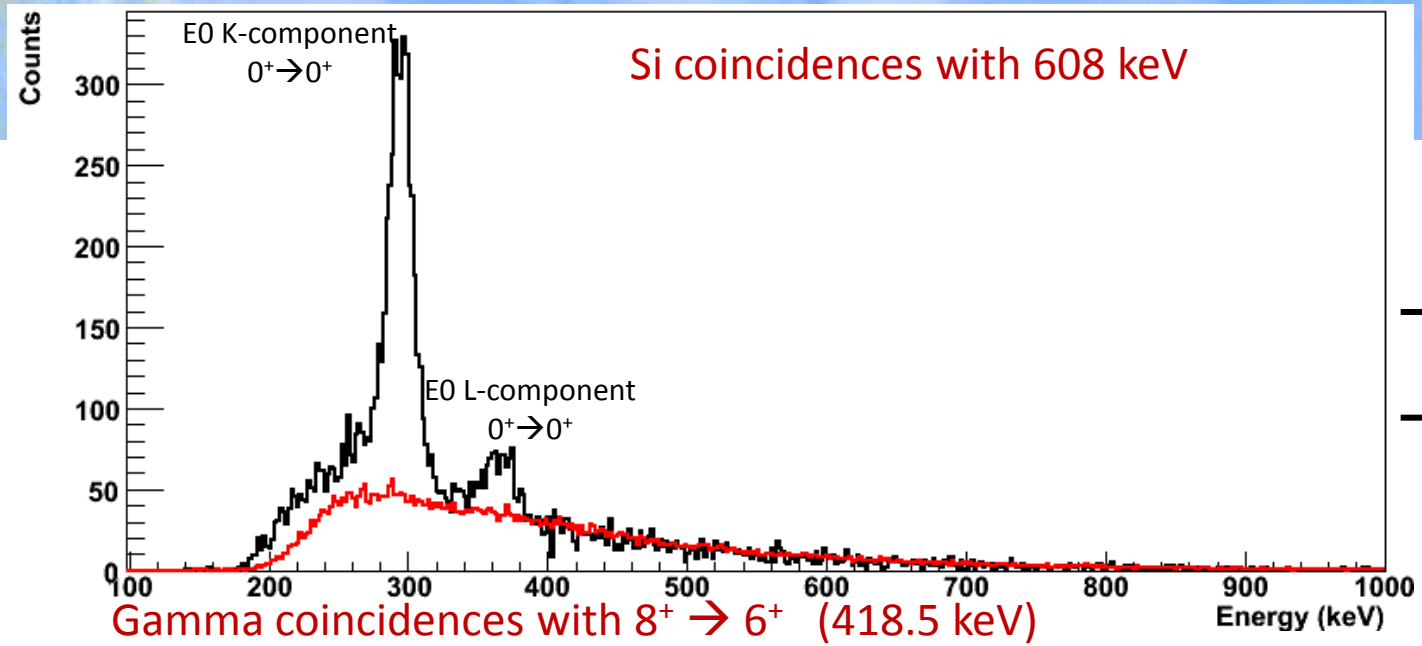
Systematics of even Hg isotopes

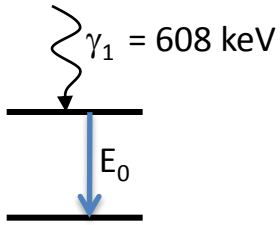
- 0_2^+ and 2_2^+ confirm minimum of prolate band in ^{182}Hg
- 2_3^+ (bandhead of γ vibrational band of prolate band follows the systematics of $^{182\text{-}186}$Hg)
- Configuration mixing



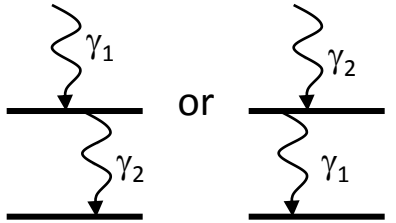


γγ and Si-γ coincidences

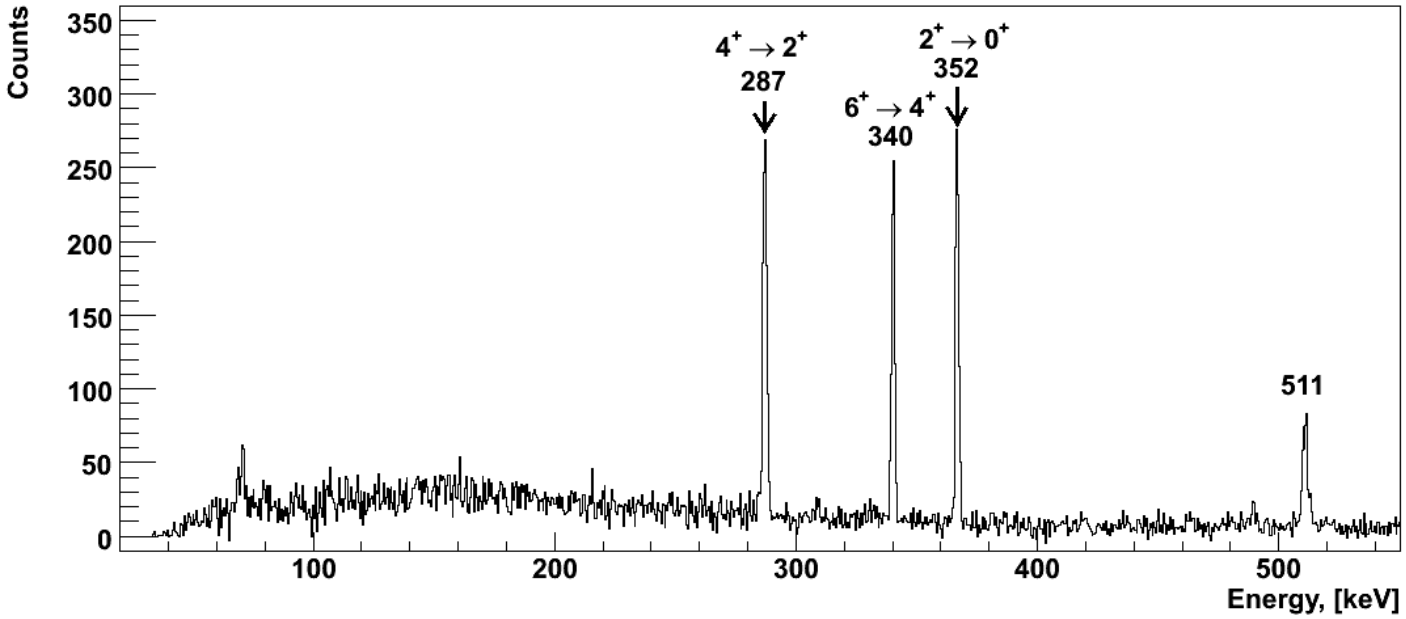




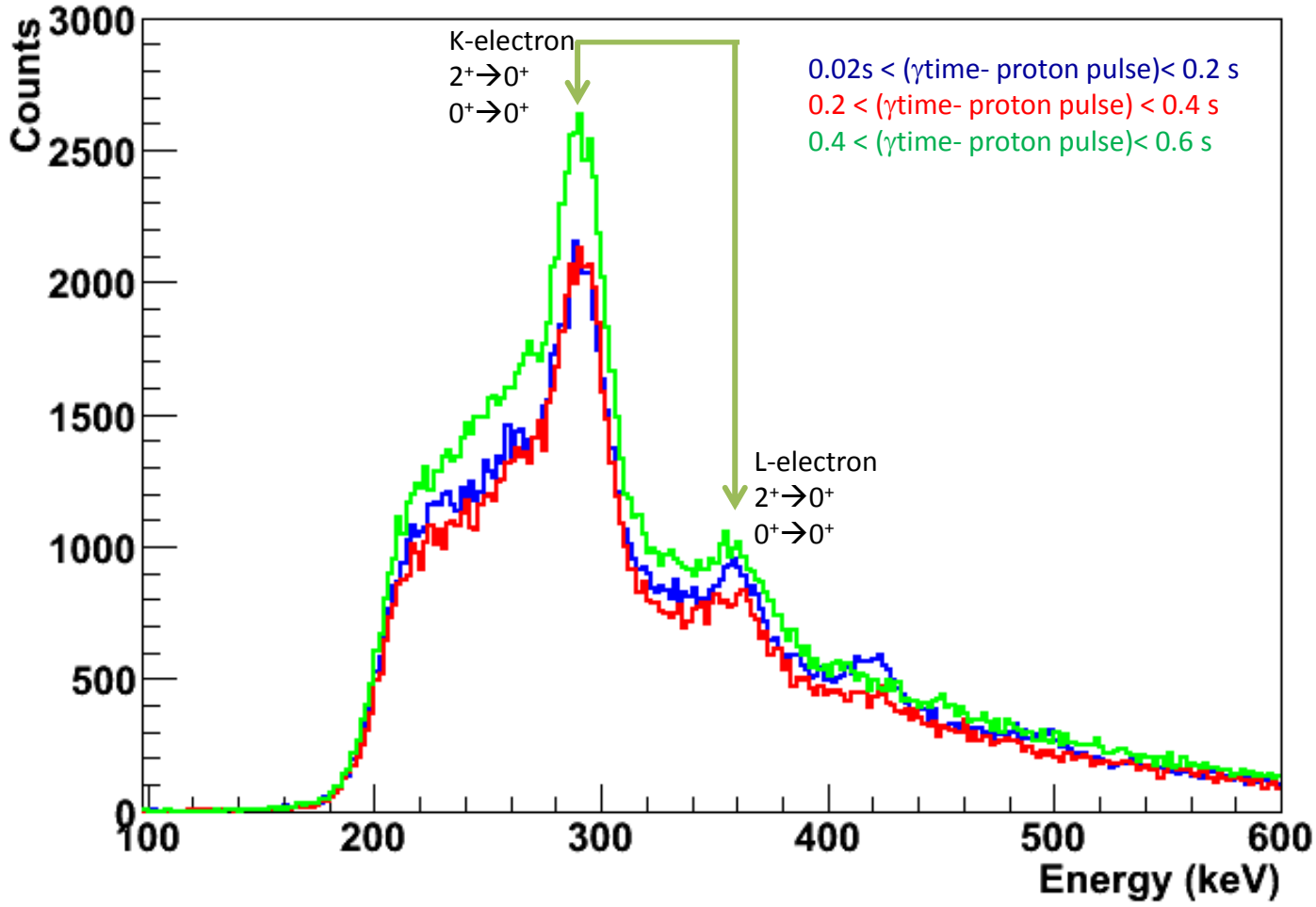
γ1 - γ2 coincident:



Gamma coincidences with $8^+ \rightarrow 6^+$ (418.5 keV)



Silicon Spectrum Time Gated: Surface Ionized data

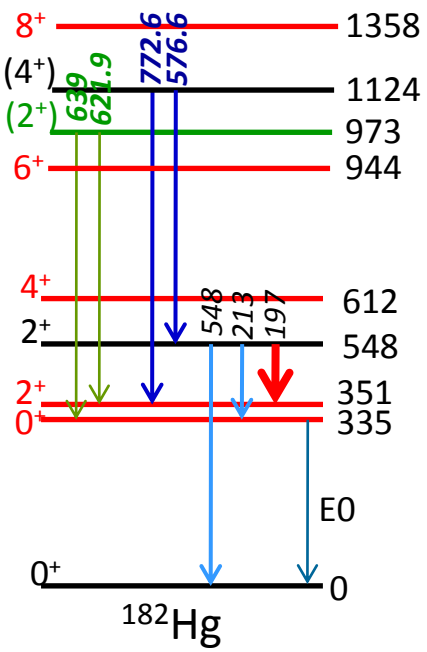


Result: 0_2^+, 2_3^+ and level mixing

0_2^+ state: 335 keV

- identified by looking at Si-γ coincidences
- already placed at 328 (12) keV from α-decay of ^{186}Pb [1]
- γ rays coincident with this Si energy: 639 keV

[1] J.Wauters et al., *Phys. Rev. C*, 50 (1994) 2768



2_3^+ state: 973 keV

- based on unambiguous coincidence relations
- band-head of γ vibrational band on top of prolate band
- $2_3^+ \rightarrow 2_2^+$ (621.9 keV): no E0 component

4_2^+ state: 1124 keV

- suggested in [2] but the 772.6 transition could not be seen
- from the energy systematics of the even-even Hg isotopes is a good candidate for 4^+ member of the oblate band

[2] M. Scheck et al., *Phys. Rev. C*, 81 (2010) 014319

$2_2^+ \rightarrow 2^+$ transition: 197 keV

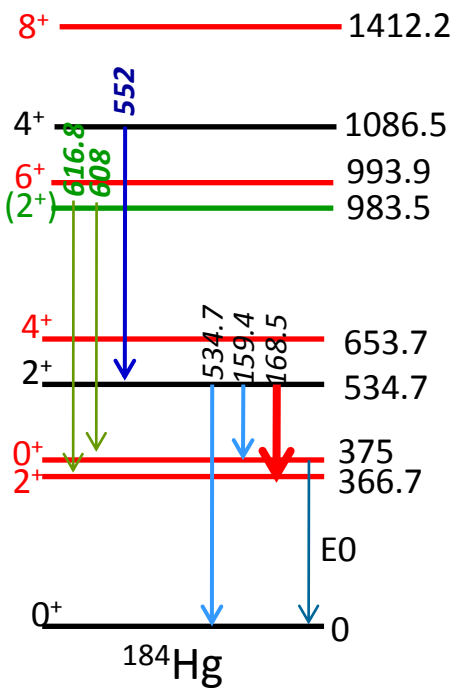
- important E0 component (**ICC = $\frac{I_{CE}}{I_\gamma}$ = 4.2 (8)**)
- the two levels are mixed;
- the two levels have different deformation

Evidence for shape coexistence: transitions with E0 components are a model-independent signature of the mixing of configurations with different mean-square radii

Result II: 0_2^+, 2_3^+ and level mixing

0_2^+ state: 375 keV

- identified by looking at Si-γ coincidences
- γ rays coincident with this Si energy: 608 keV



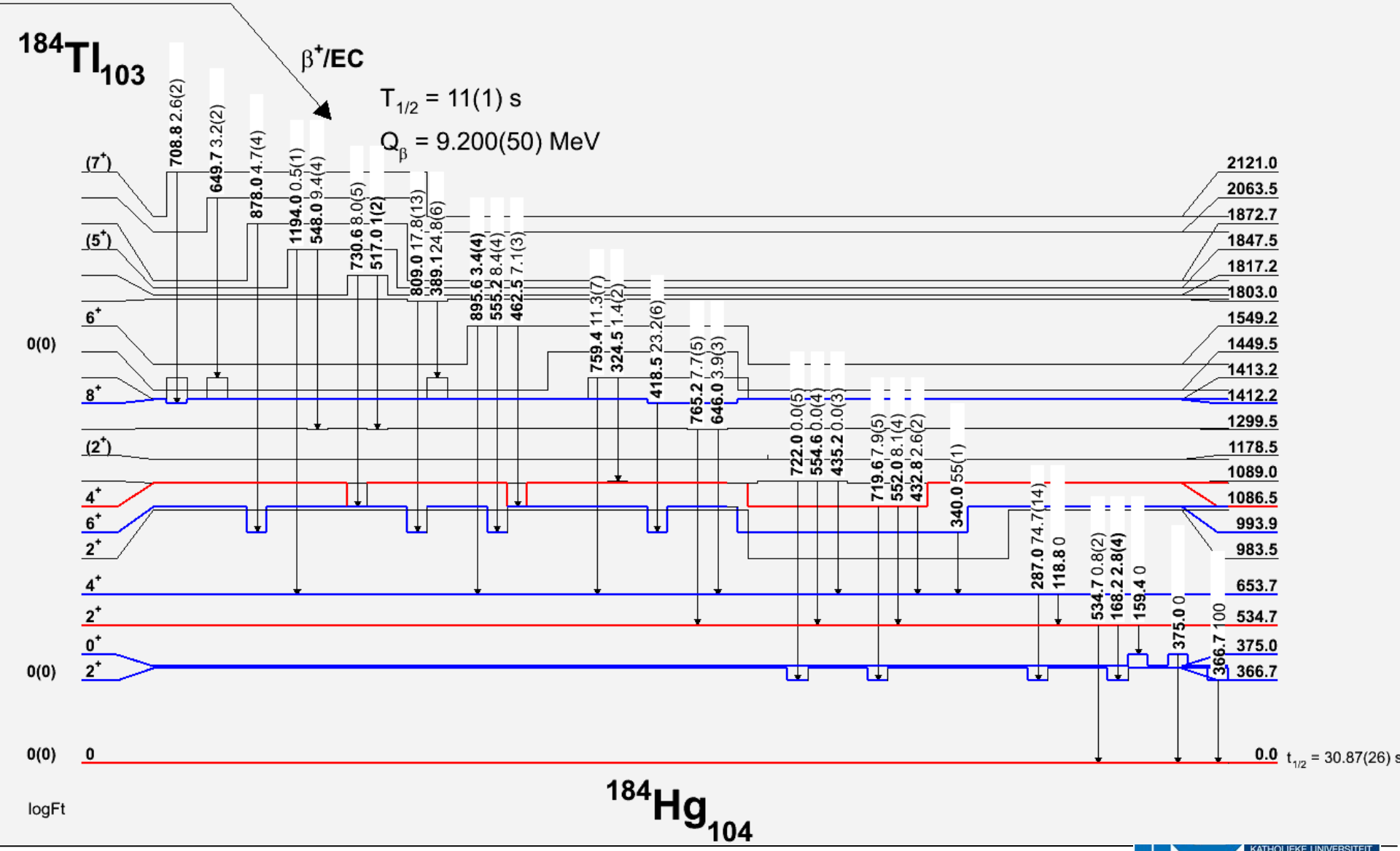
2_3^+ state: 983.5 keV

- based on unambiguous coincidence relations
- band-head of γ vibrational band on top of prolate band
-

$2_2^+ \rightarrow 2^+$ transition: 168.5 keV

- important E0 component (**ICC = $\frac{I_{CE}}{I_\gamma}$ = 23 (5)**)

Evidence for shape coexistence: transitions with E0 components are a model-independent signature of the mixing of configurations with different mean-square radii


184Tl103
β+/EC
T1/2 = 11(1) s
Qβ = 9.200(50) MeV
(7+)
(5+)
6+
0(0)
8+
(2+)
4+
6+
2+
4+
2+
0+
0(0)
2+
0(0)
0
logFt
708.8 2.6(2)
649.7 3.2(2)
878.0 4.7(4)
1194.0 0.5(1)
548.0 9.4(4)
730.6 8.0(5)
517.0 1(2)
809.0 17.8(13)
389.1 24.8(6)
895.6 3.4(4)
555.2 8.4(4)
462.5 7.1(3)
759.4 11.3(7)
324.5 1.4(2)
418.5 23.2(6)
765.2 7.7(5)
646.0 3.9(3)
722.0 0.0(5)
554.6 0.0(4)
435.2 0.0(3)
719.6 7.9(5)
552.0 8.1(4)
432.8 2.6(2)
340.0 55(1)
287.0 74.7(14)
118.8 0
534.7 0.8(2)
168.2 2.8(4)
159.4 0
375.0 0
366.7 100
2121.0
2063.5
1872.7
1847.5
1817.2
1803.0
1549.2
1449.5
1413.2
1412.2
1299.5
1178.5
1089.0
1086.5
993.9
983.5
653.7
534.7
375.0
366.7
0.0
t1/2 = 30.87(26) s
184Hg104