

Coulomb excitation of $^{182,184}\text{Hg}$: shape coexistence in the neutron-deficient lead region

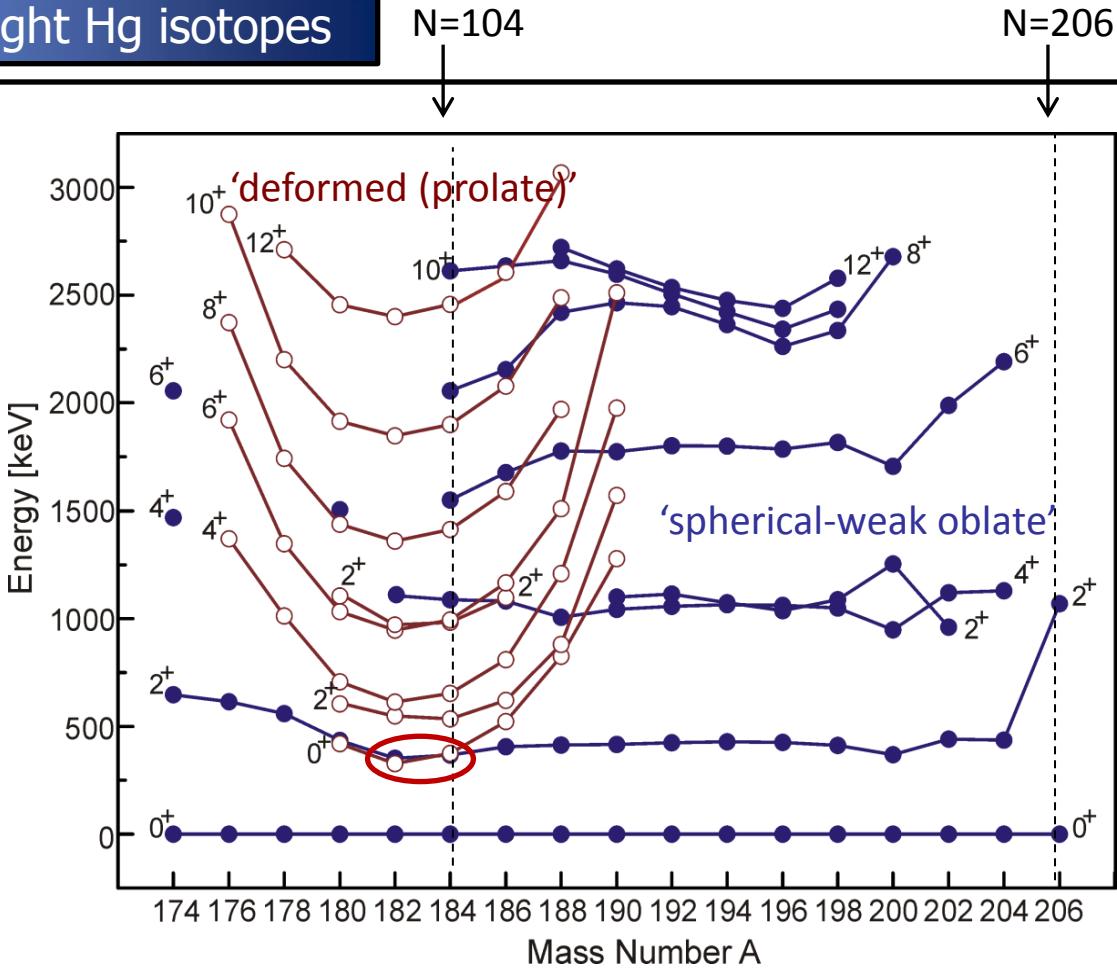
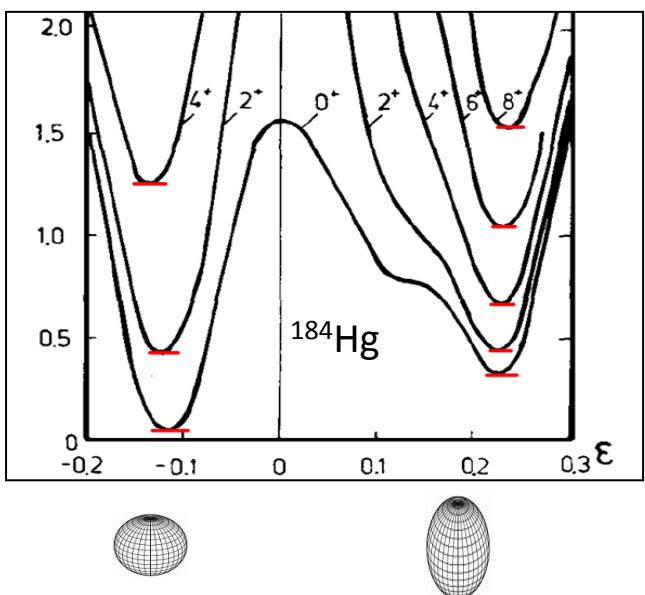
- Motivation
- Results from previous experiments @ REX-ISOLDE
- Comparison with theory
- Proposed HIE-ISOLDE experiment

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Co-spokepersons: Janne Pakarinen (University of Jyväskylä),
David Joss (University of Liverpool),
David Jenkins (University of York)

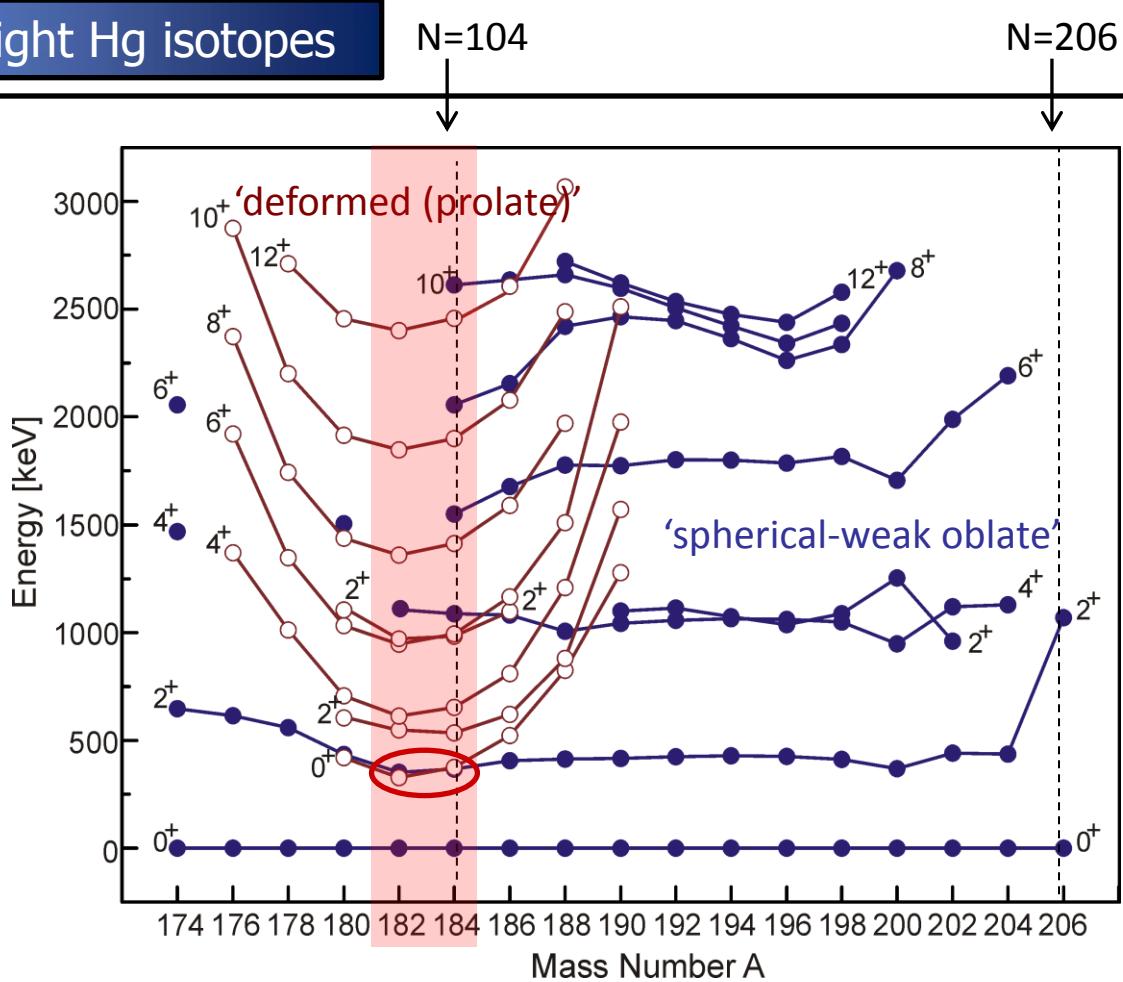
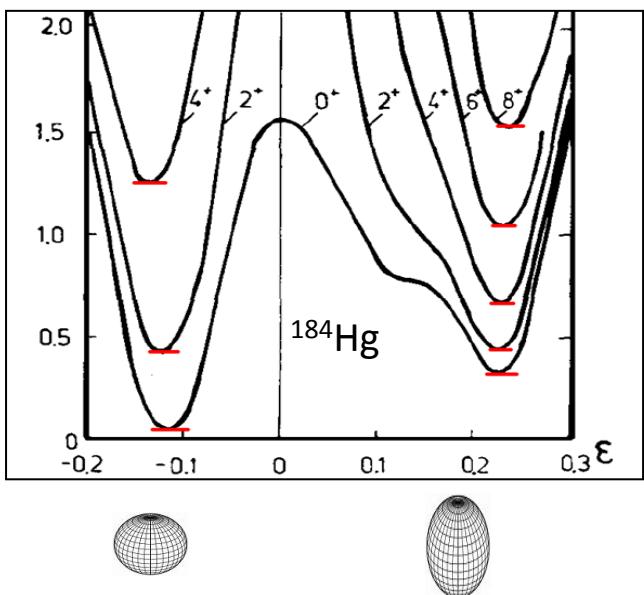
Shape coexistence in the light Hg isotopes

- S. Frauendorf *Phys.Lett. B* 55 (1975) 365
- W. Nazarewicz et al. *Phys.Lett.B* 305 (1993) 195
- M. Bender, P.-H. Heneen , P.-G. Reinhard
Rev. of Mod. Phys. 75 (2003) 121
- K. Heyde and J. Wood
Rev. of Mod. Phys. 83 (2011) 1467

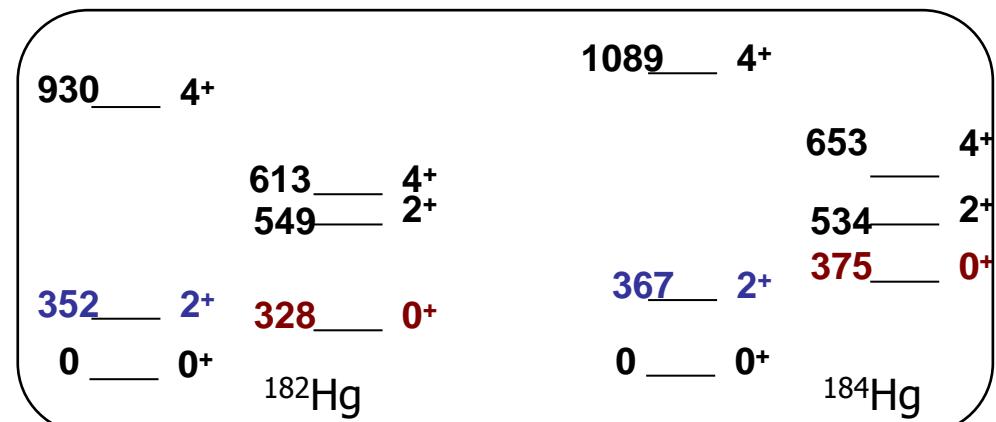


Shape coexistence in the light Hg isotopes

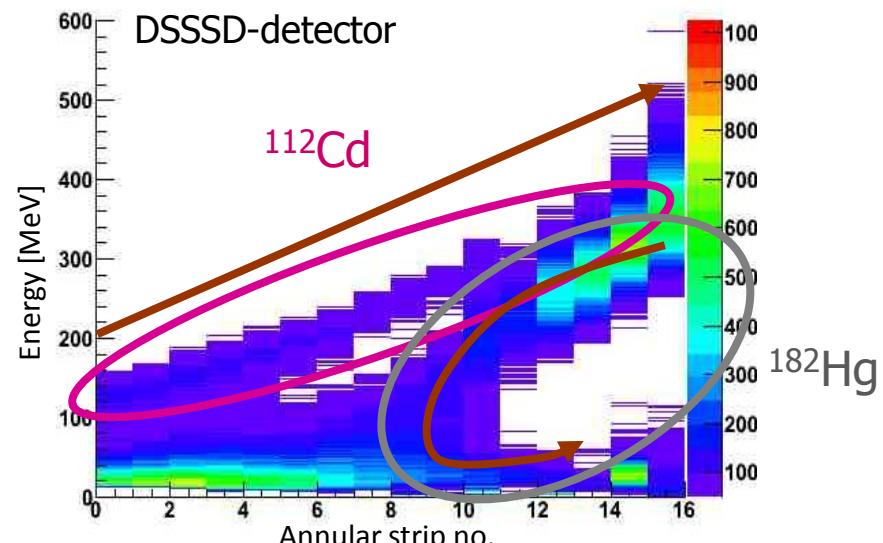
- S. Frauendorf *Phys.Lett. B* 55 (1975) 365
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- Strong mixing in the low-energy level scheme
- 'oblate' – 'prolate': model dependent interpretation
→ Coulomb excitation



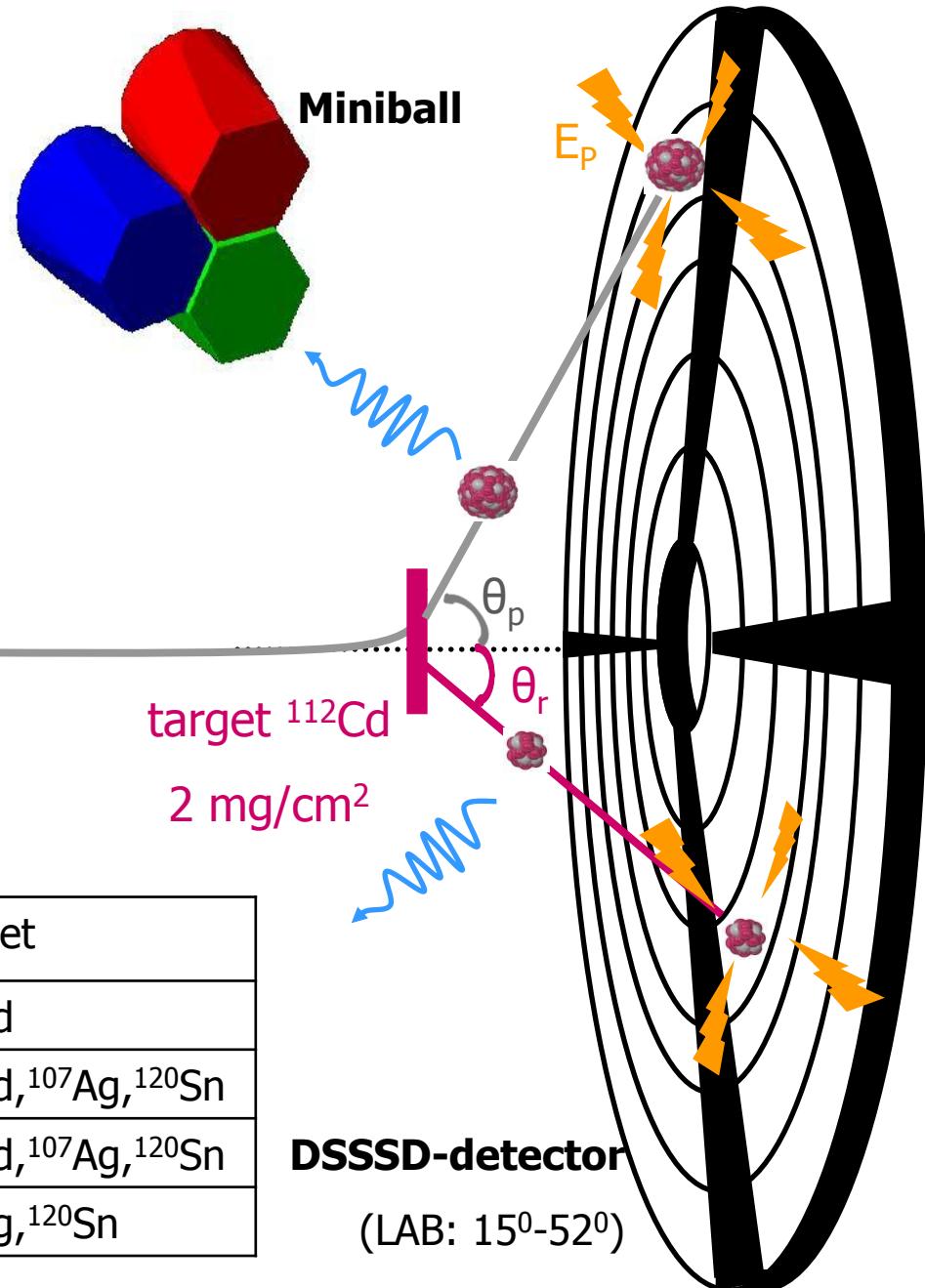
Previous experiments: Coulomb excitation of $^{182,184,186,188}\text{Hg}$ @ 2.85 MeV/A



^{182}Hg
2.85 MeV/u

target ^{112}Cd
 2 mg/cm^2

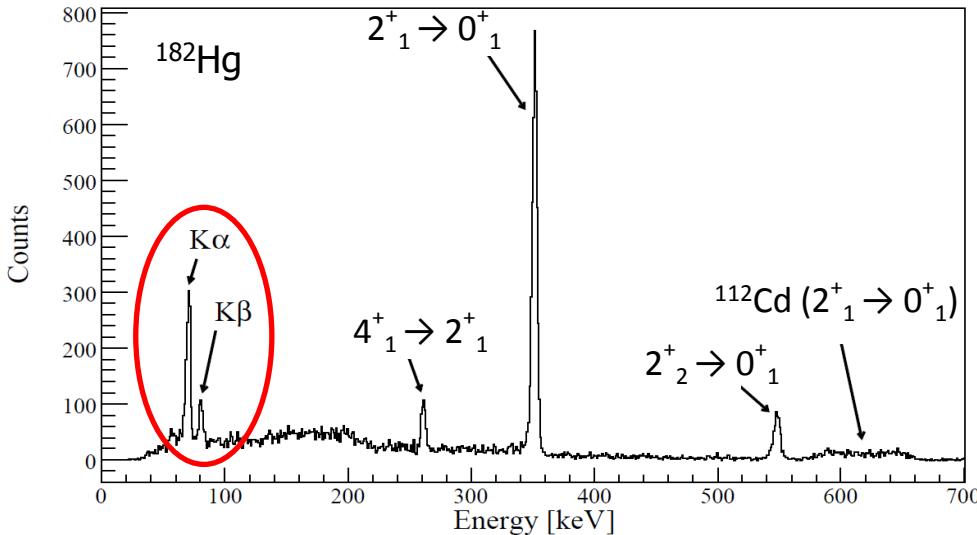
DSSSD-detector
(LAB: 15° - 52°)



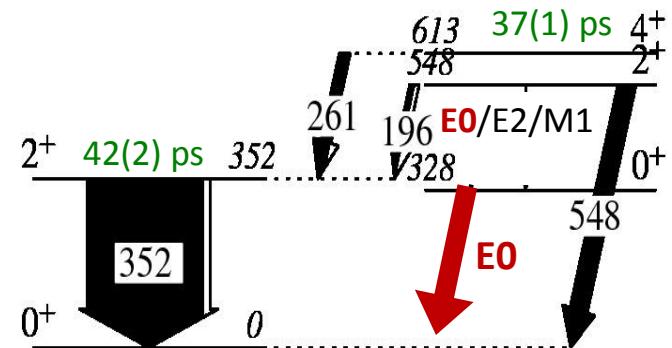
Isotope	Summer 2007	Summer 2008	Target
^{182}Hg		4.9×10^3 pps	^{112}Cd
^{184}Hg	1.0×10^3 pps	1.0×10^5 pps	$^{112}\text{Cd}, ^{107}\text{Ag}, ^{120}\text{Sn}$
^{186}Hg	2.0×10^5 pps	2.5×10^5 pps	$^{114}\text{Cd}, ^{107}\text{Ag}, ^{120}\text{Sn}$
^{188}Hg	2.5×10^5 pps	3.1×10^5 pps	$^{107}\text{Ag}, ^{120}\text{Sn}$

Previous experiments: observed gamma ray yields

Summer of 2008: ^{182}Hg @2.85 MeV/u on ^{112}Cd target



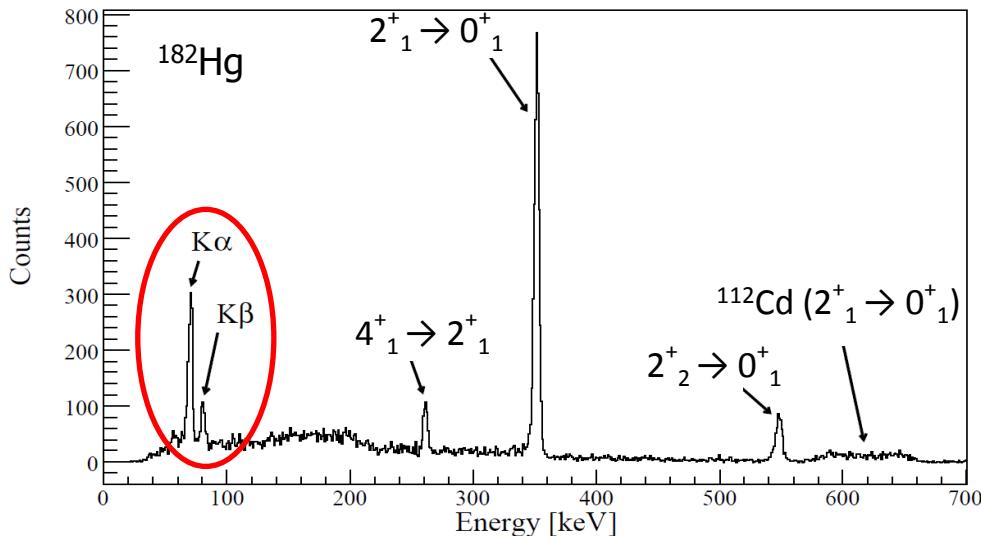
^{182}Hg



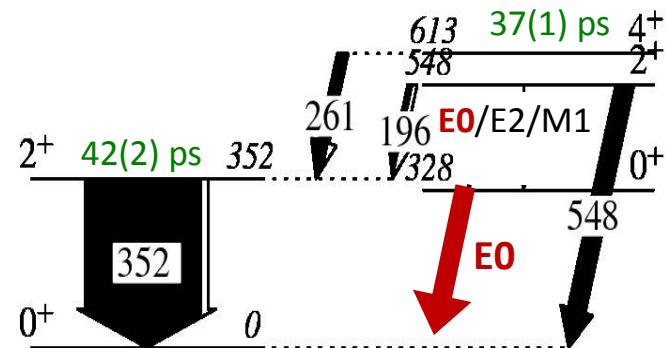
- the K α and K β X rays originating from mercury.
- attributed to the converted $2^+_2 \rightarrow 2^+_1$ transition and the E0 ($0^+_2 \rightarrow 0^+_1$) deexcitation

Converted $2^+_2 \rightarrow 2^+_1$ transitions in $^{182,184}\text{Hg}$

Summer of 2008: ^{182}Hg @2.85 MeV/u on ^{112}Cd target



^{182}Hg



- the K_α and K_β X rays originating from mercury.
- attributed to the converted $2^+_2 \rightarrow 2^+_1$ transition and the E0 ($0^+_2 \rightarrow 0^+_1$) deexcitation
- mixing between different states \rightarrow strongly converted $2^+_2 \rightarrow 2^+_1$ transitions:

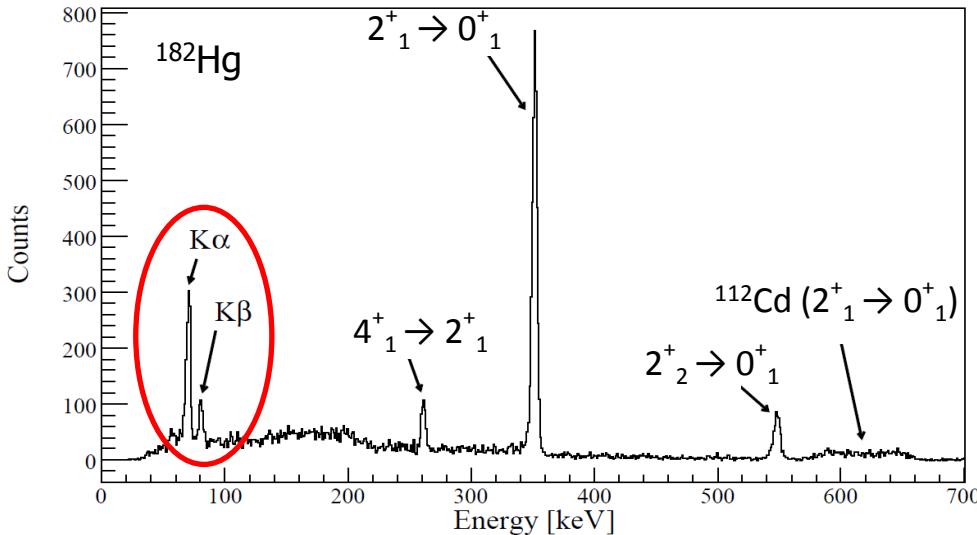
(E. Rapisarda, β decay studies of $^{182,184}\text{Tl}$ isotopes)

$$^{182}\text{Hg}: \alpha_{CE} (2^+_2 \rightarrow 2^+_1) = 4.2(8)$$

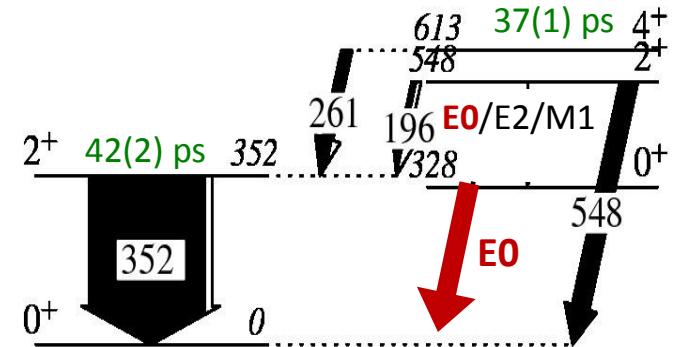
$$^{184}\text{Hg}: \alpha_{CE} (2^+_2 \rightarrow 2^+_1) = 23(5)$$

GOSIA analysis

Summer of 2008: ^{182}Hg @2.85 MeV/u on ^{112}Cd target



^{182}Hg



- the K_α and K_β X rays originating from mercury.
- attributed to the converted $2^+_2 \rightarrow 2^+_1$ transition and the $E0 (0^+_2 \rightarrow 0^+_1)$ deexcitation
- mixing between different states \rightarrow strongly converted $2^+_2 \rightarrow 2^+_1$ transitions:

(E. Rapisarda, β decay studies of $^{182,184}\text{Tl}$ isotopes)

$$^{182}\text{Hg}: \alpha_{CE} (2^+_2 \rightarrow 2^+_1) = 4.2(8)$$

$$^{184}\text{Hg}: \alpha_{CE} (2^+_2 \rightarrow 2^+_1) = 23(5)$$

Combined analysis of the **Coulex** data

+ τ measurements

RDDS measurements at Jyvaskyla and ANL
(T. Grahn, L. Gaffney, A. Petts, M. Hackstein)

+ BR and $\alpha_{CE} (2^+_2 \rightarrow 2^+_1)$ (E. Rapisarda)

GOSIA

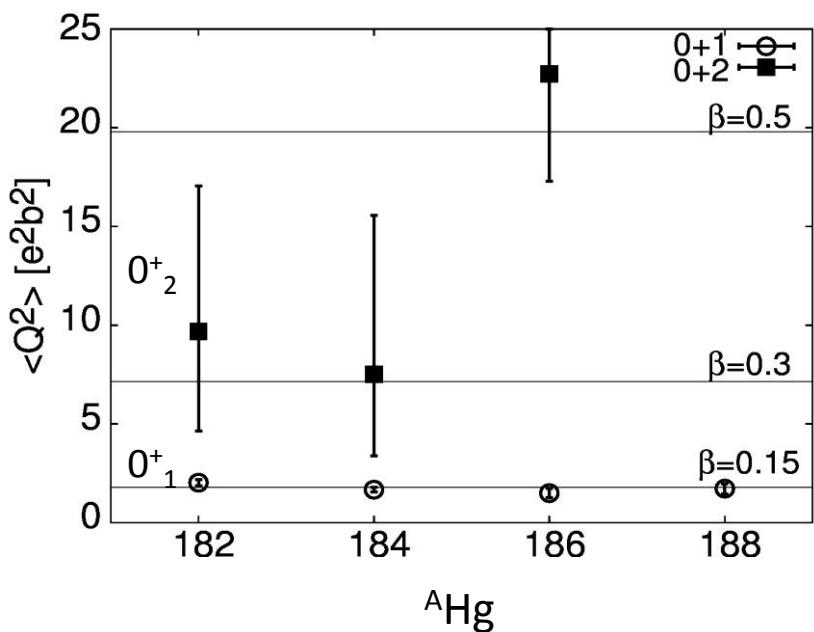
$\langle i | | E2 | | f \rangle, Q_s(2^+)$ in $^{182-188}\text{Hg}$

Results: quadrupole deformation parameters

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

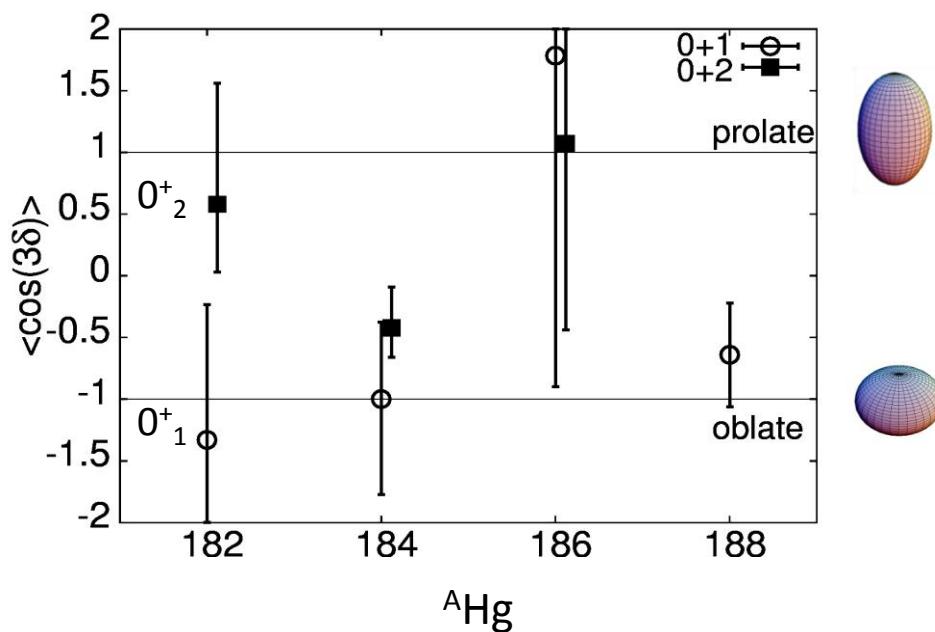
Overall deformation $\sim \beta \sim \langle Q^2 \rangle$:

$\sim \text{BE2}(2^+_i \rightarrow 0^+_{1,2})$



Triaxiality $\sim \gamma \sim \langle \cos 3\delta \rangle$:

\sim relative signs of $\langle 0^+_2 || E2 || 2^+_i \rangle$, $\langle 2^+_i || E2 || 2^+_{j'} \rangle$, $Q_{\text{sp}}(2^+)$

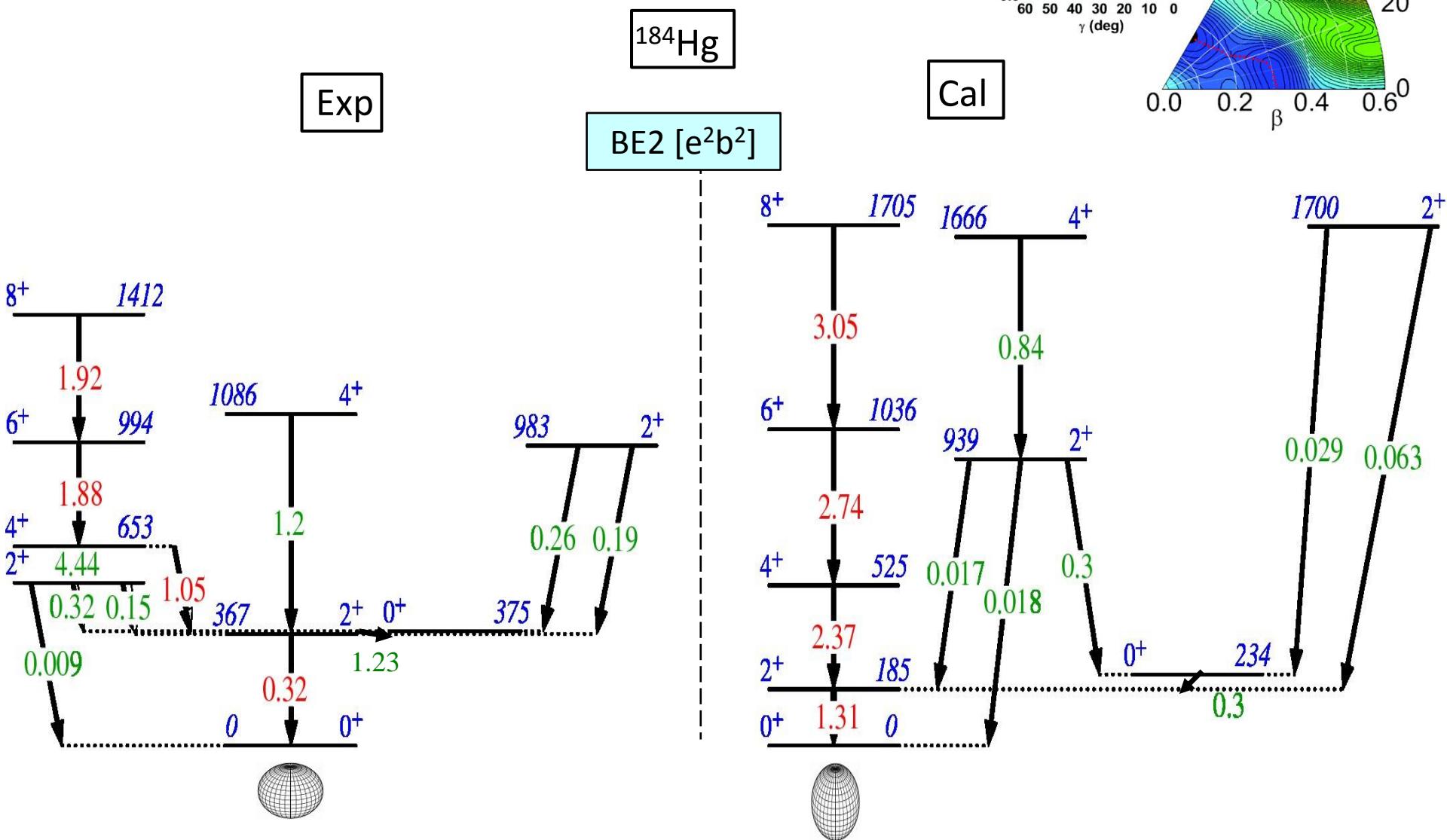


Large uncertainties related with \longrightarrow

$\langle i E2 f \rangle$	^{182}Hg	^{184}Hg
$\langle 2^+_1 E2 2^+_1 \rangle$	-0.07 (-1.29, +1.17)	1.4 (-1.2, +1.8)
$\langle 2^+_2 E2 2^+_2 \rangle$	1.22 (-0.71, +1.20)	-3.4 (+1.9, -1.7)
$\langle 0^+_2 E2 2^+_1 \rangle$		-2.48 ± 1.38

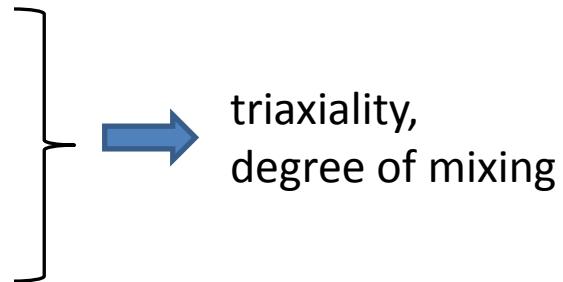
Comparison with theory

Beyond mean field calculations: P.-H. Heenen, M. Bender



Physics aims:

1. establish a deformation of the 0^+_2 state in $^{182,184}\text{Hg}$.
2. reduce the error bars of the $Q_{\text{sp}} (2^+_1)$ and $Q_{\text{sp}} (2^+_2)$
3. $B(E2)$'s between non-yrast states up to the spin 8^+



How to reach it ? → COULEX with HIE-ISOLDE beams

BEAM:

^{182}Hg : 10^4 pps, 4MeV/A

^{184}Hg : 10^5 pps, 4MeV/A

TARGET:

^{120}Sn (2 mg/cm²)

- highest possible Z vs well kinematic separation
- high $E(2^+_1) = 1.17$ MeV
- no overlapping γ 's from projectile / target excitation

SET-UP:

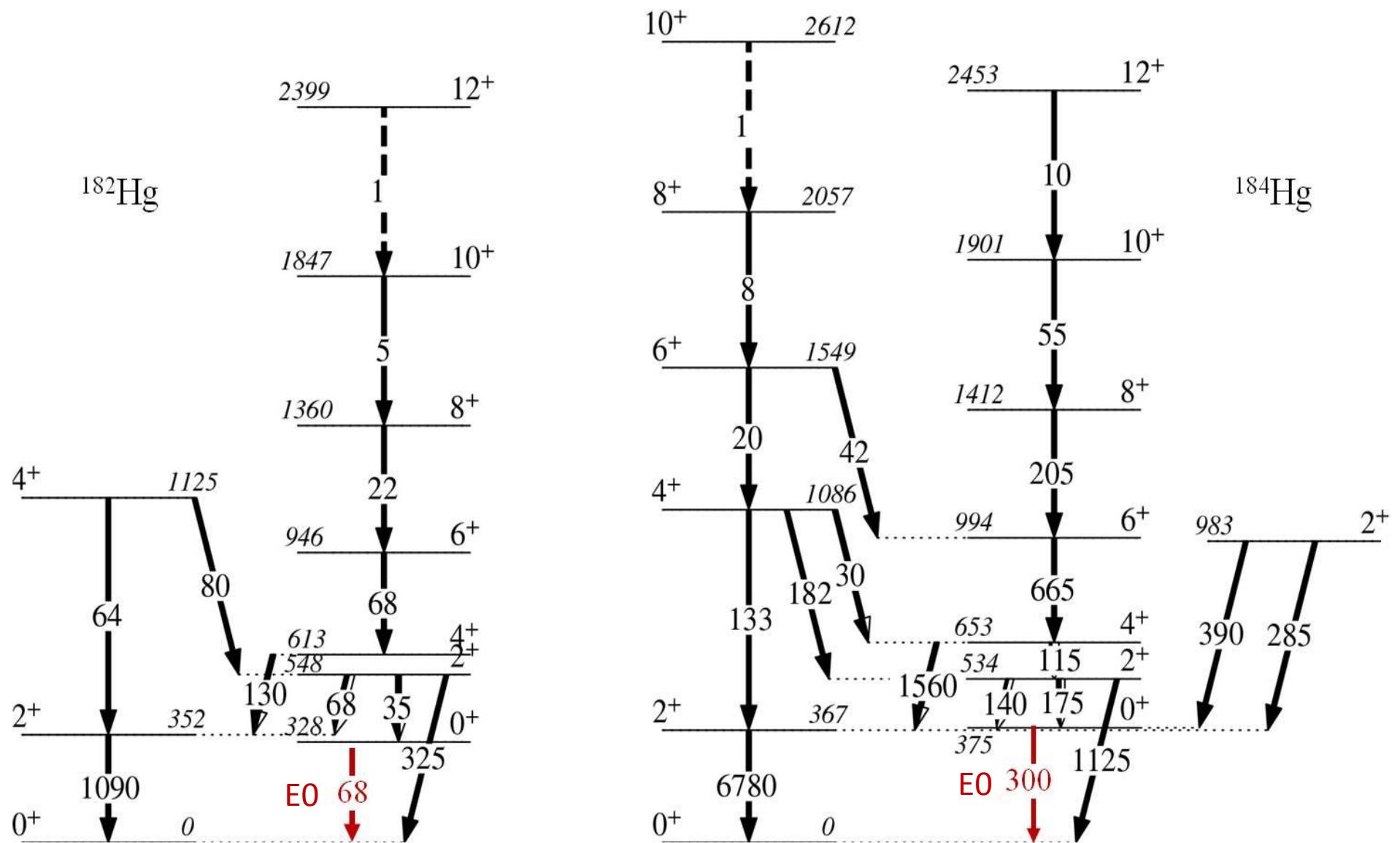
1. MINIBALL + DSSSD set-up (15° - 52° in LAB) => p- γ coincidences
2. MINIBALL + SPEDE* electron spectrometer => γ -e detection => $E0 (0^+_1 \rightarrow 0^+_2)$

* J. Pakarinen et al., HIE-ISOLDE Letter of Intent I-107

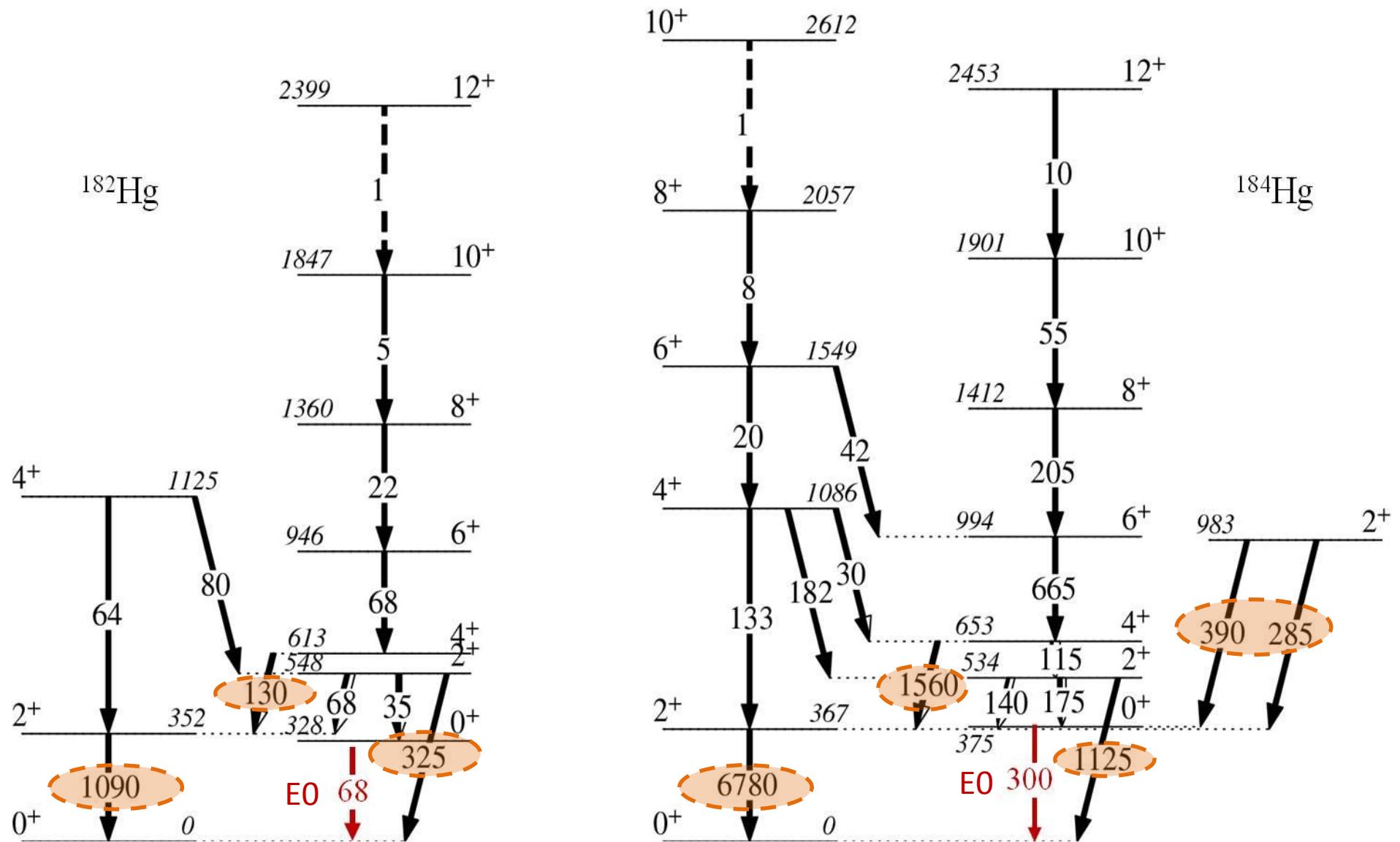
Counting rates:

GOSIA calculations based on the results from previous COULEX / lifetime measurements.

HIE-ISOLDE experiment – counting rates / shift



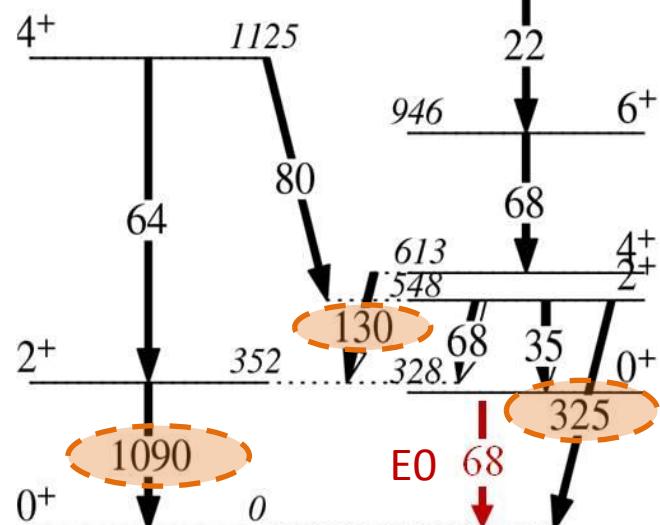
HIE-ISOLDE experiment – counting rates / shift



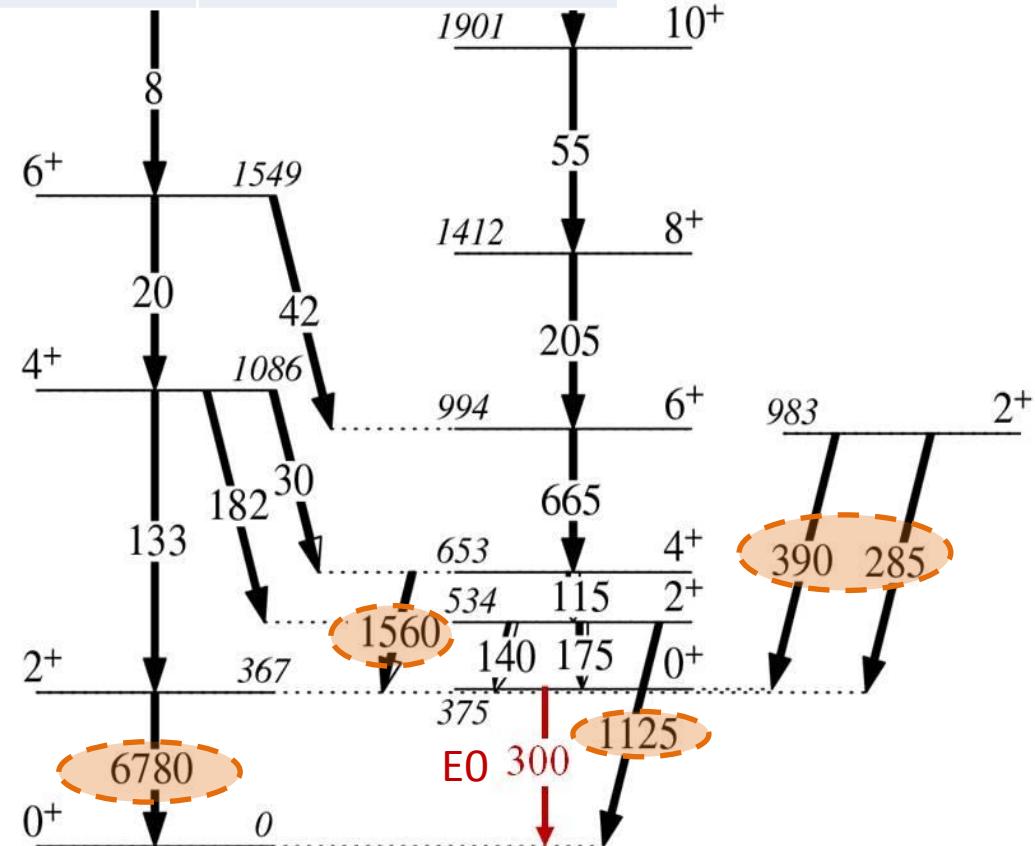
HIE-ISOLDE experiment – beam time request

	Beam intensity	Energy	Number of shifts	
^{182}Hg	10^4 pps	4 MeV/A	24	
^{184}Hg	10^5 pps	4 MeV/A	4	12^+
setting – up			2	
			30 shifts	

^{182}Hg



^{184}Hg



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Additional slides

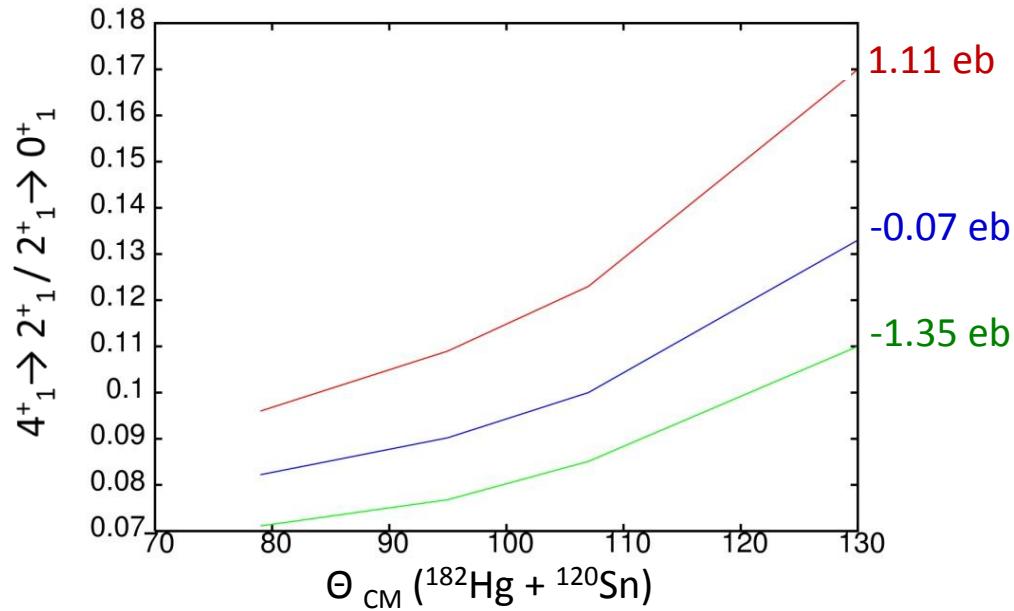
4MeV/A vs 2.85 MeV/A COULEX experiments – counting rates

transition	^{182}Hg 2.85 MeV/A	^{182}Hg 4 MeV/A	^{182}Hg 2.85 MeV/A	^{182}Hg 4 MeV/A
	Counts/shift	Counts/shift	Total (^{112}Cd target) (~14 shifts)	Total (^{112}Cd target) (24 shifts)
$2^+_1 \rightarrow 0^+_1$	276	1 090	3 812 (68)	26 160
$2^+_2 \rightarrow 0^+_1$	40	130	556 (27)	3 120
$4^+_1 \rightarrow 2^+_1$	23	325	319 (42)	7 800
$2^+_2 \rightarrow 2^+_1$	10	68	139 (60)	1 632
$0^+_2 \rightarrow 0^+_1$	45	68	624 (96)	1632

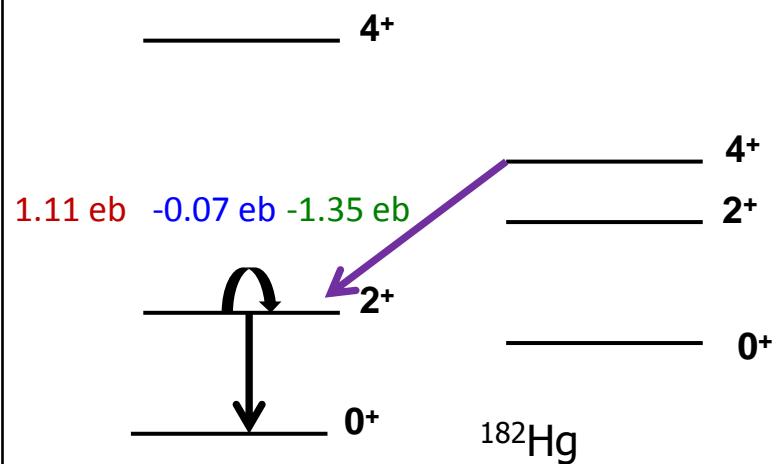
transition	^{184}Hg 2.85 MeV/A	^{184}Hg 4 MeV/A	^{184}Hg 2.85 MeV/A	^{184}Hg 4 MeV/A
	Counts/shift	Counts/shift	Total (^{112}Cd , ^{120}Sn , ^{107}Ag targets) (~11 shifts)	Total (4 shifts)
$2^+_1 \rightarrow 0^+_1$	2 258	6 780	24 838	27 120
$2^+_2 \rightarrow 0^+_1$	131	1 125	1 048	4 500
$4^+_1 \rightarrow 2^+_1$	175	1 560	1 925	6 240
$4^+_2 \rightarrow 2^+_2$	3	182	33	728
$2^+_3 \rightarrow 2^+_1$ & $2^+_3 \rightarrow 0^+_2$	2	390 285	22	1 560 1 140
$0^+_2 \rightarrow 0^+_1$ (^{112}Cd)	125		200 (118)	
$0^+_2 \rightarrow 0^+_1$ (^{120}Sn)	6.5	300	47 (137)	1200

Distinguish between positive – zero- negative value of the $\langle 2^+_1 || E2 || 2^+_1 \rangle$

$Q_{sp}(2^+_1)$ influences on the $2^+_1 \rightarrow 0^+_1$ and $4^+_1 \rightarrow 2^+_1$ yields:

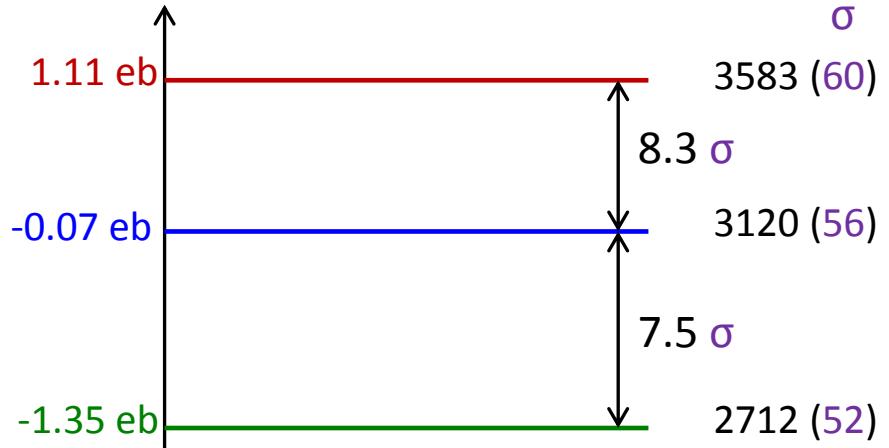


$$\langle 2^+_1 || E2 || 2^+_1 \rangle = -0.07 \text{ (129, 117)}$$

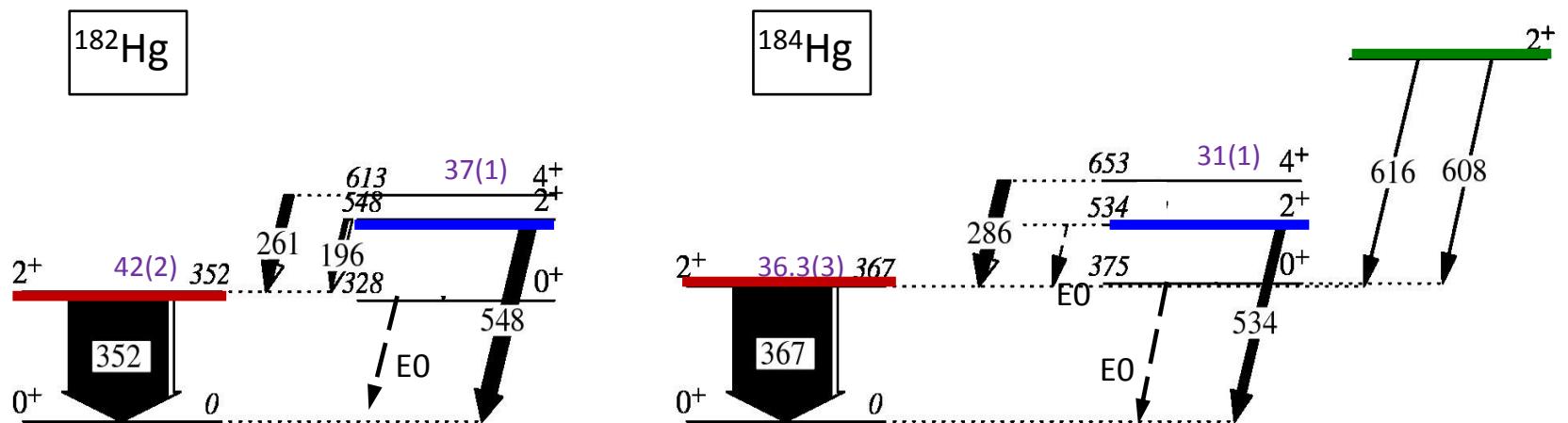


counts / 24 shifts

$$\langle 2^+_1 || E2 || 2^+_1 \rangle$$



The $4^+_1 \rightarrow 2^+_1$ yield changes at the level of **7-8 σ** with the statistics accumulated during 24 shifts.



Matrix elements [eb]	^{182}Hg	^{184}Hg
$\langle 0^+_1 E2 2^+_1 \rangle$	1.29 (3; 4)	1.27 (4; 5)
$\langle 2^+_1 E2 4^+_1 \rangle$	-3.71 (6)	-3.07 (6)
$\langle 0^+_1 E2 2^+_2 \rangle$	0.60 (3)	-0.21 (2)
$\langle 0^+_2 E2 2^+_1 \rangle$	-2.65 (15)	-2.14 (138)
$\langle 0^+_2 E2 2^+_2 \rangle$	1.63 (22; 19)	1.27 (23; 17)
$\langle 2^+_1 E2 2^+_2 \rangle$	2.74 (23; 18)	-0.88 (7; 8)
$\langle 2^+_1 E2 2^+_1 \rangle$	-0.07 (129; 117)	1.4 (12; 18)
$\langle 2^+_2 E2 2^+_2 \rangle$	1.22 (71; 120)	-3.4 (19; 17)
$\langle 2^+_1 E2 2^+_3 \rangle$		-0.96 (25)
$\langle 0^+_2 E2 2^+_3 \rangle$		 1.15 (30)

Quadrupole sum rules invariants: $\langle Q^2 \rangle$ and $\langle \cos 3\delta \rangle$

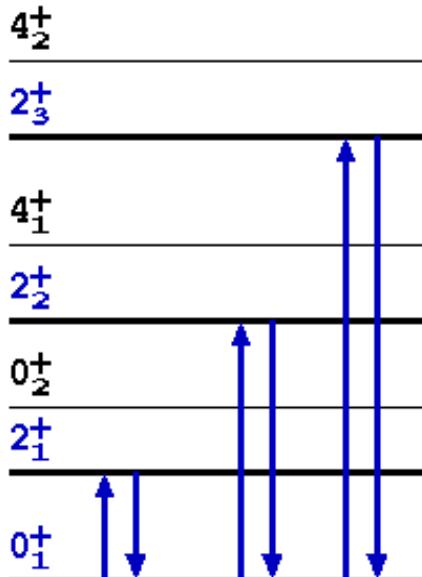
Parametrization of the E2 operator

$$\rightarrow \left\{ \begin{array}{lcl} E(2, 0) & = & Q \cos \delta, \\ E(2, 1) & = & E(2, -1) = 0, \\ E(2, 2) & = & E(2, -2) = \frac{1}{\sqrt{2}} \cdot Q \sin \delta. \end{array} \right.$$

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

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

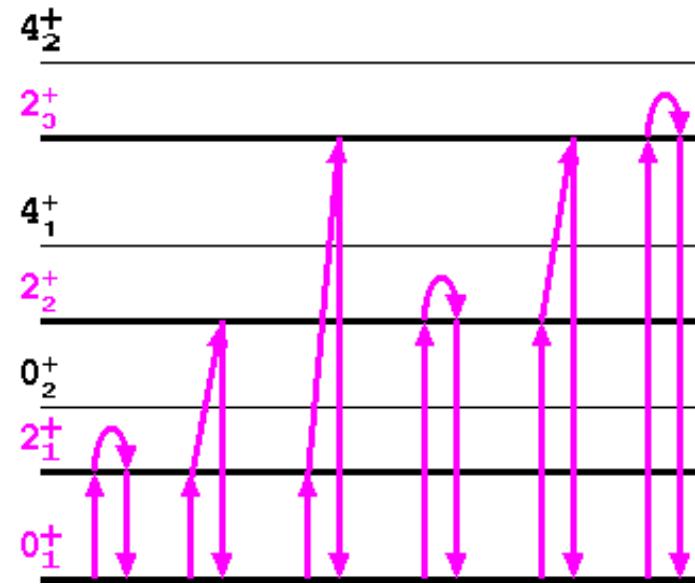
Overall deformation $\sim \beta \sim \langle Q^2 \rangle$:



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

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

Triaxiality $\sim \gamma \sim \langle \cos 3\delta \rangle$:



Appendix A. The quadrupole invariants for an uniformly charged ellipsoid

From Eqs. (21) and (22) the formulae for the two basic collective quadrupole invariants are:

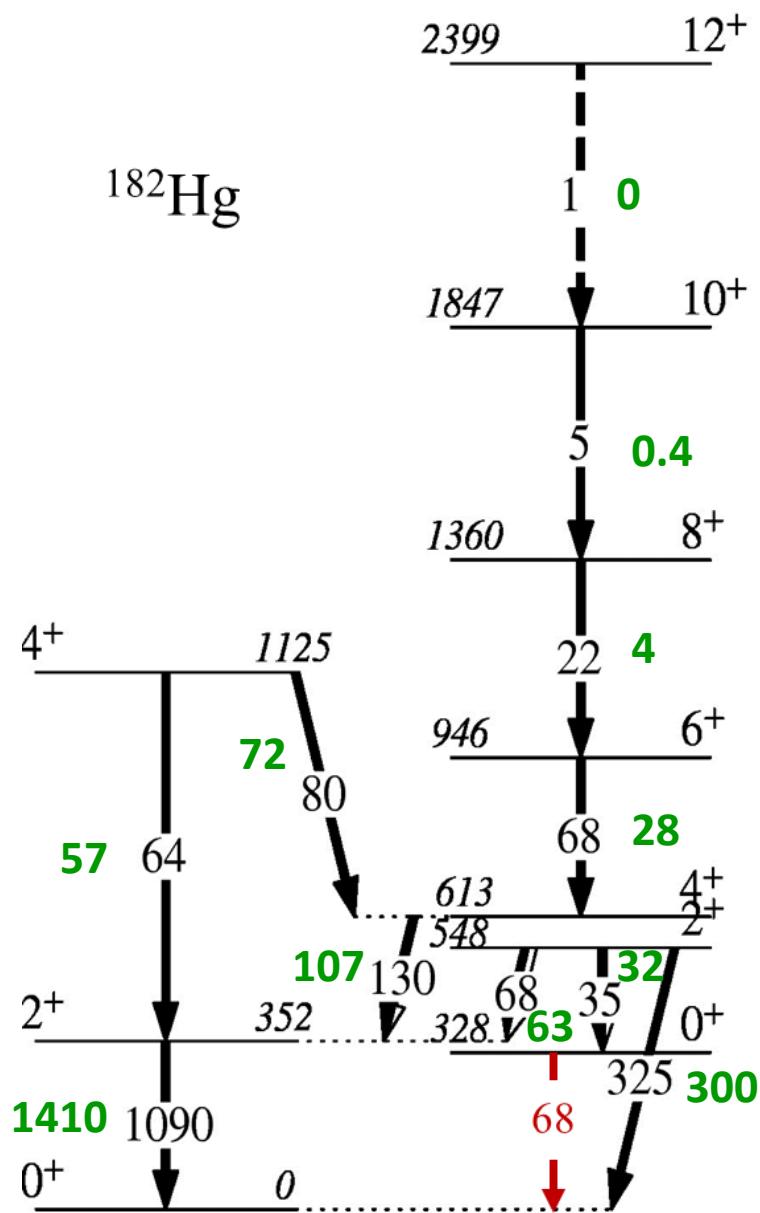
$$Q^2 = \left(\frac{3}{4\pi} Z R^2 \right)^2 (\beta^2 + 2C\beta^3 \cos 3\gamma + C^2\beta^4) \\ \approx q_0^2 (\beta^2 + 2C\beta^3 \cos 3\gamma + 17C^2\beta^4) + \mathcal{O}(\beta^5), \quad (\text{A.1})$$

$$Q^3 \cos 3\delta = \left(\frac{3}{4\pi} Z R^2 \right)^3 (\beta^3 \cos 3\gamma + 3C\beta^4 + 3C^2\beta^5 \cos 3\gamma + 2C^3\beta^6 \cos^2 3\gamma - C^3\beta^6) \\ \approx q_0^3 (\beta^3 \cos 3\gamma + 3C\beta^4 + 27C^2\beta^5 \cos 3\gamma - 30C^3\beta^6 \cos^2 3\gamma + 71C^3\beta^6) \\ + \mathcal{O}(\beta^7), \quad (\text{A.2})$$

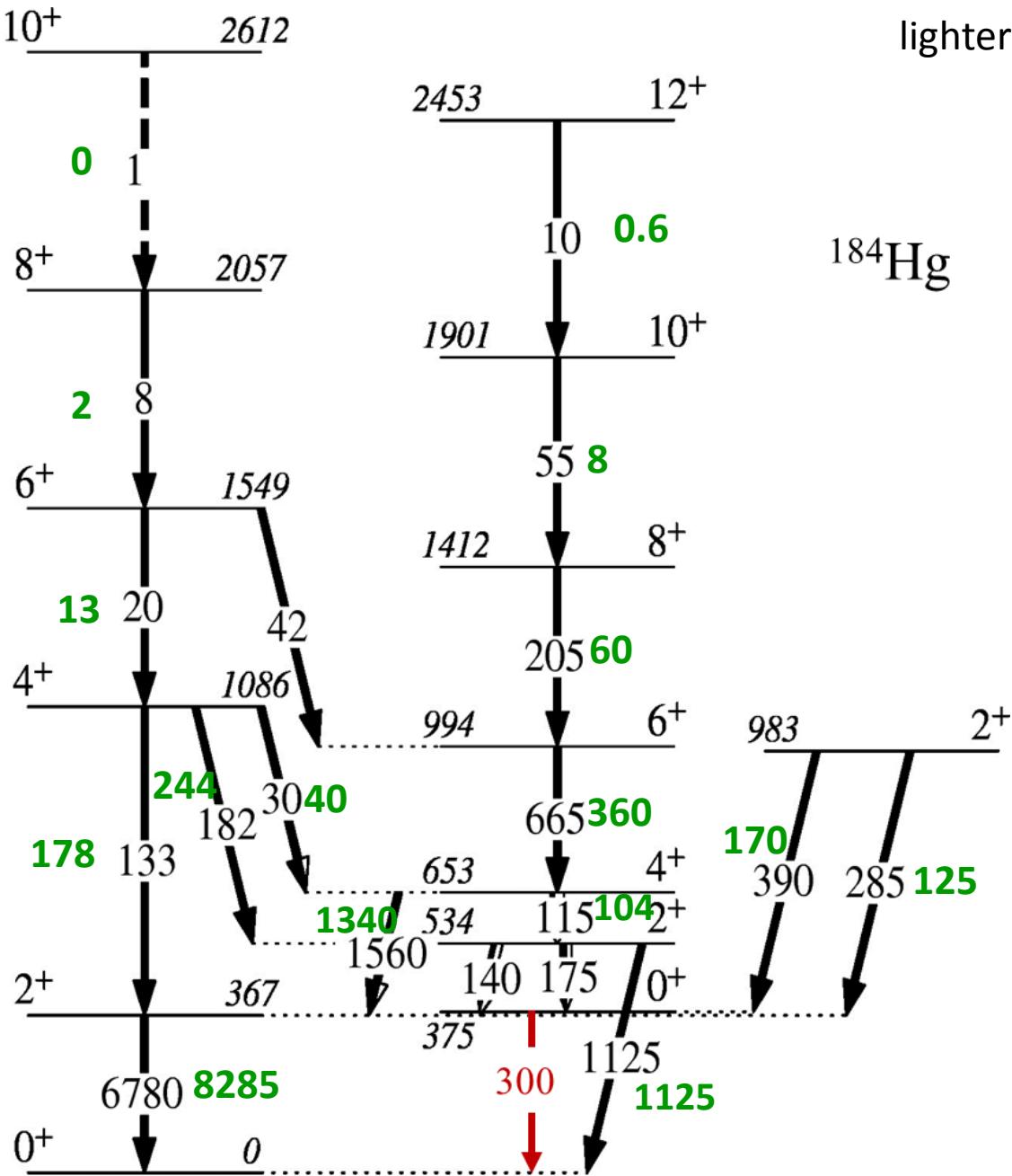
where $q_0 = (3/4\pi) Z R_0^2$. Calculating the mean values of invariants in β and γ in a given state the mean values of the quadrupole invariants can be calculated from the above formulas. To calculate

Is there anything to gain measuring on the lighter target (^{58}Ni , Z=28) ?

		$^{182}\text{Hg} + ^{120}\text{Sn}$	$^{182}\text{Hg} + ^{58}\text{Ni}$
II	IF	Relative intensity	Relative intensity
12+1	10+1	7,3E-04	2,2E-05
10+1	8+1	4,6E-03	3,0E-04
8+1	6+1	2,0E-02	3,0E-03
4+2	2+1	5,8E-02	4,0E-02
4+2	2+2	7,5E-02	5,1E-02
6+1	4+1	6,2E-02	2,0E-02
4+1	2+1	1,2E-01	7,6E-02
2+2	0+1	3,0E-01	2,1E-01
2+2	2+1	6,2E-02	4,5E-02
2+2	0+2	3,2E-02	2,3E-02
2+1	0+1	1,0E+00	1,0E+00

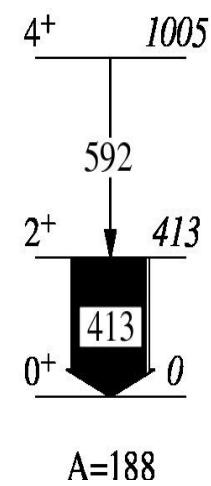
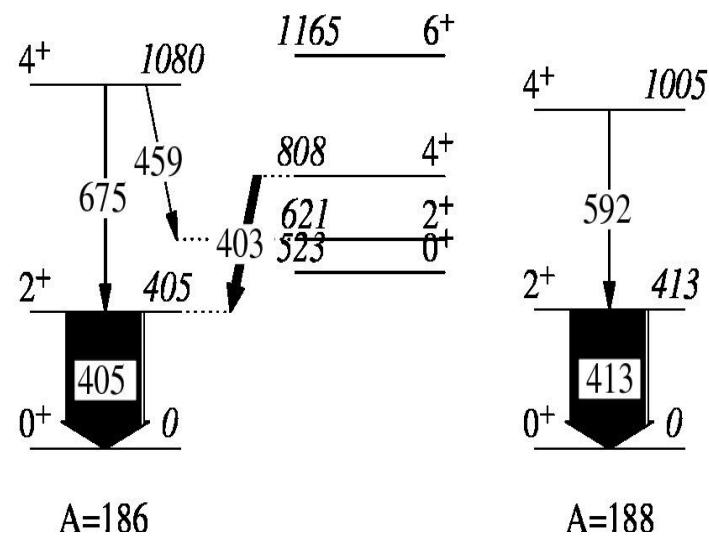
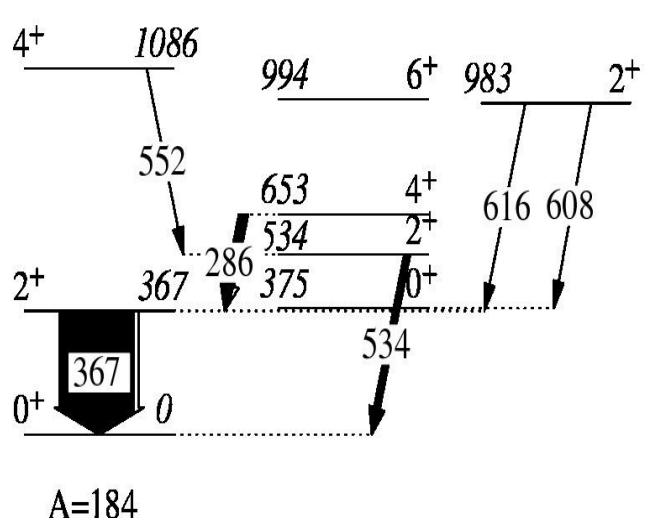
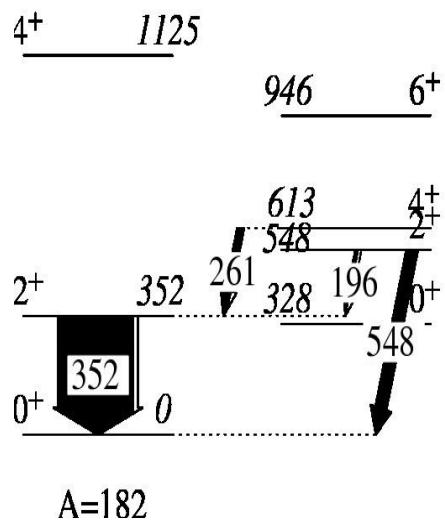


Is there anything to gain measuring on the lighter target (^{58}Ni , Z=28) ?

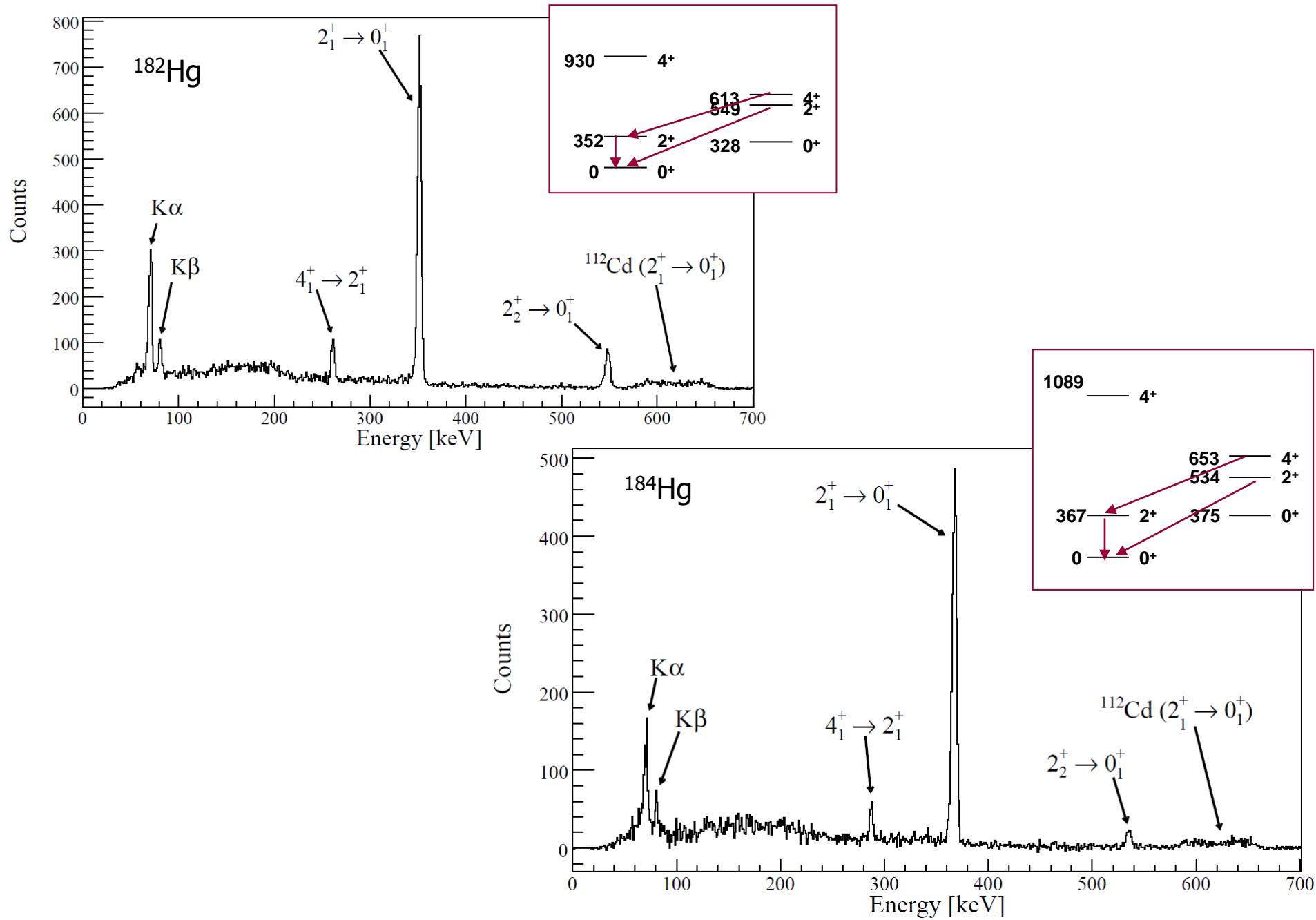


		$^{184}\text{Hg} + ^{120}\text{Sn}$	$^{184}\text{Hg} + ^{58}\text{Ni}$
II	IF	Relative intensity	<u>Relative intensity</u>
8+2	6+2	1,2E-03	2,7E-04
6+2	4+2	2,9E-03	1,5E-03
4+2	2+1	2,0E-02	2,1E-02
4+2	2+2	2,7E-02	2,9E-02
2+3	0+2	5,8E-02	2,1E-02
2+3	2+2	4,2E-02	1,5E-02
6+1	4+1	9,8E-02	4,3E-02
4+1	2+1	2,3E-01	1,7E-02
2+2	0+1	1,7E-01	1,4E-01
2+2	2+1	2,1E-02	1,7E-02
2+2	0+2	2,6E-02	2,1E-02
2+1	0+1	1,0E+00	1,0E+00

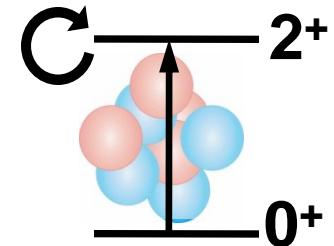
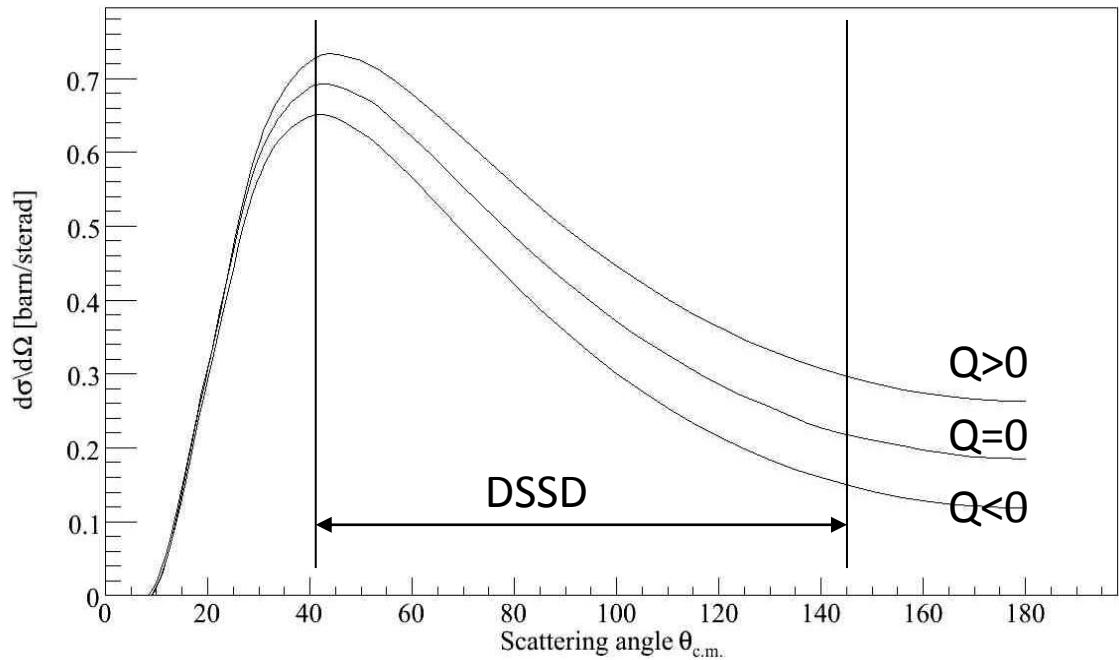
Low-energy part of the Coulomb excited level scheme of $^{182-188}\text{Hg}$



Experimental campaigns 2008: 2.85 Mev/A on ^{112}Cd target

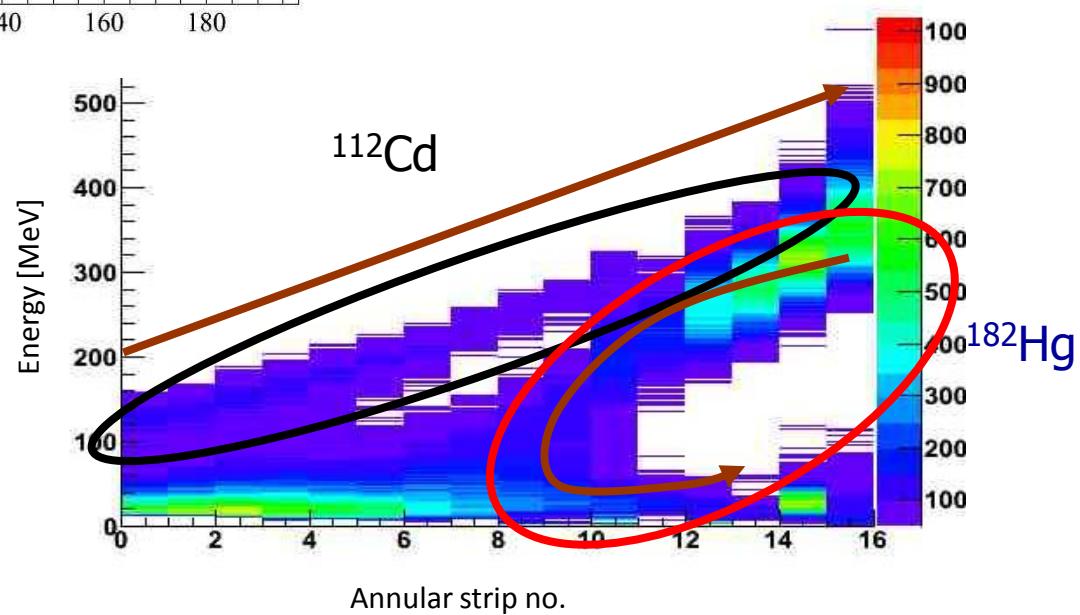


Determination of the quadrupole moment of the first excited 2^+ state



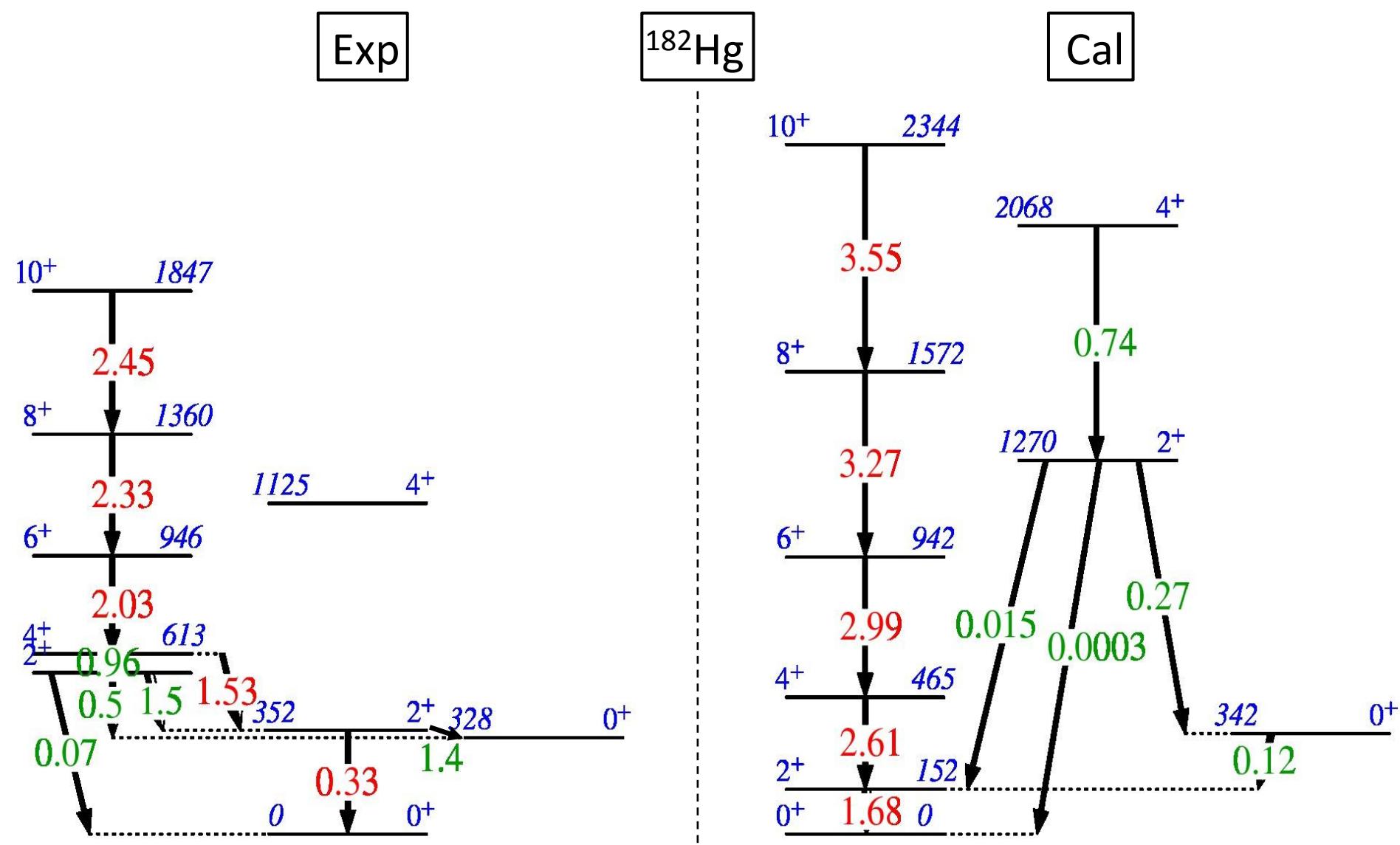
Coulex cross-section depends on **both**
 $\langle 0^+ || E2 || 2^+ \rangle$ and $\langle 2^+ || E2 || 2^+ \rangle$

Scanning the c.m. range by gating on
 different strips!



Comparison with theory – BE2 in ^{182}Hg

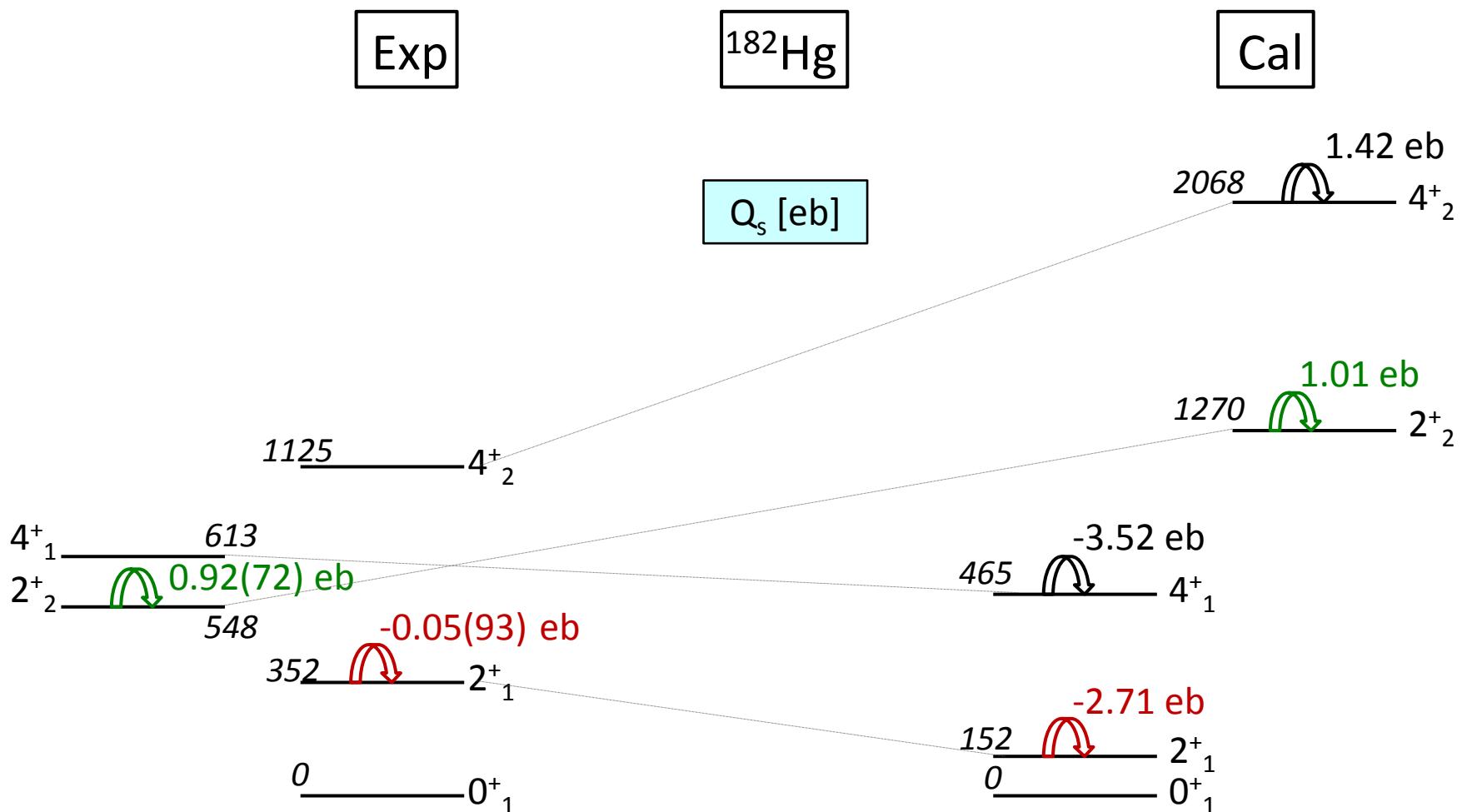
* Beyond mean field, P.-H.Heenen



a number of discrepancies: energies, transition rates – mainly $0^+_1 \rightarrow 2^+_1$ and B(E2) between non-yrast states

Comparison with theory – Q_{sp} in ^{182}Hg

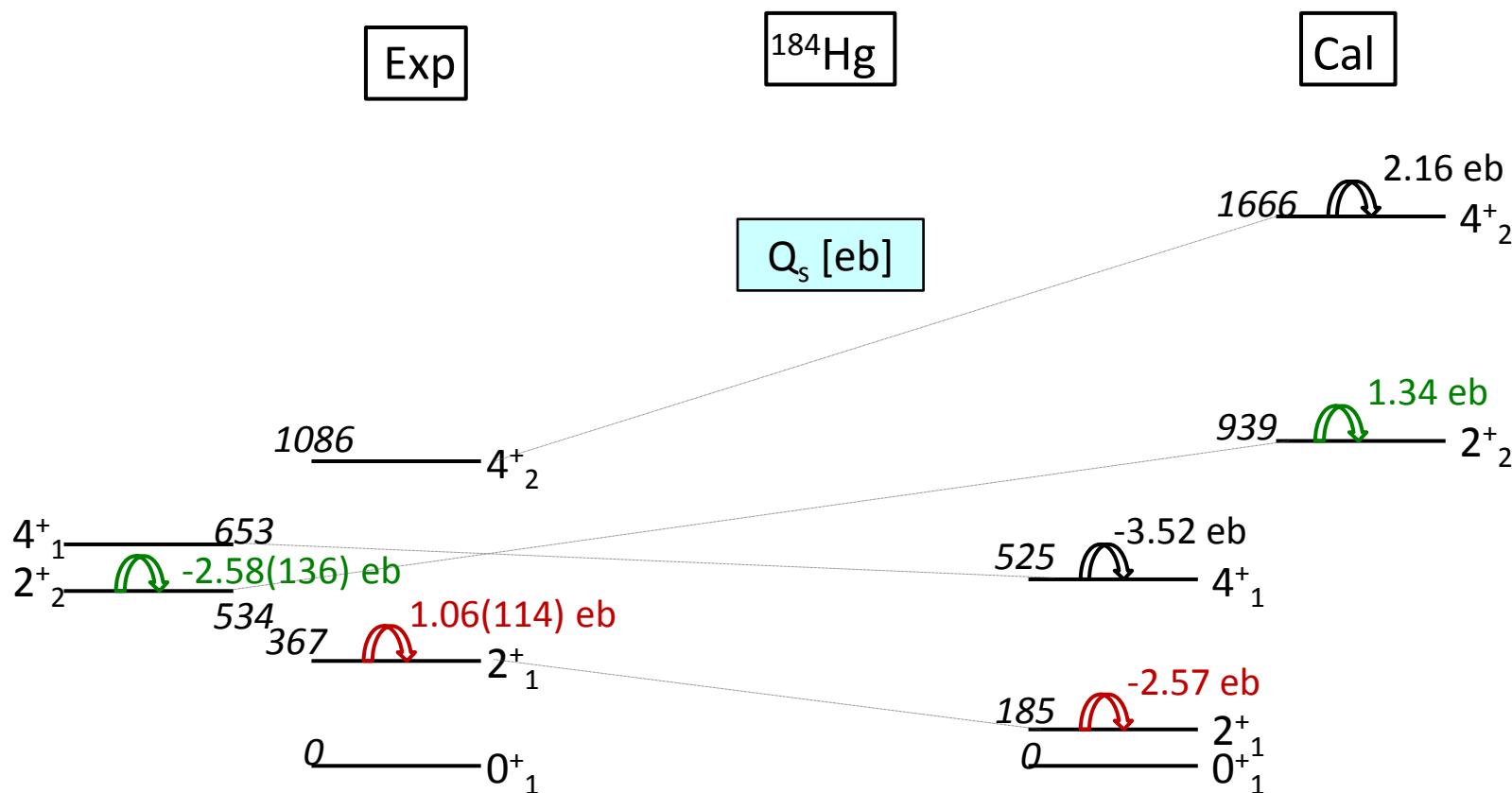
* Beyond mean field, P.-H.Heenen



$Q_{\text{sp}}(2^+_1)$ – agreement within 3σ limit
 $Q_{\text{sp}}(2^+_2)$ – agreement within 1σ limit

Comparison with theory - Q_{sp} in ^{184}Hg

* Beyond mean field, P.-H.Heenen

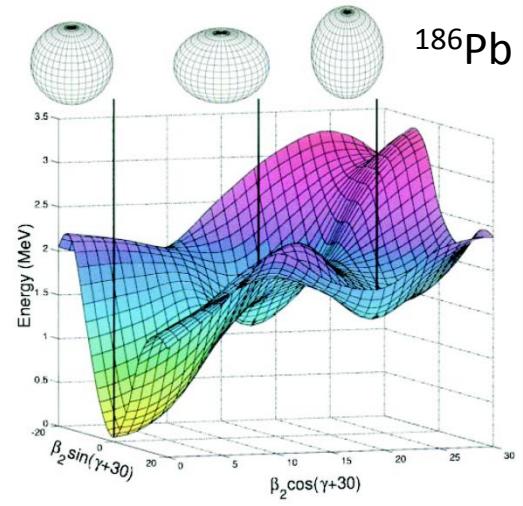
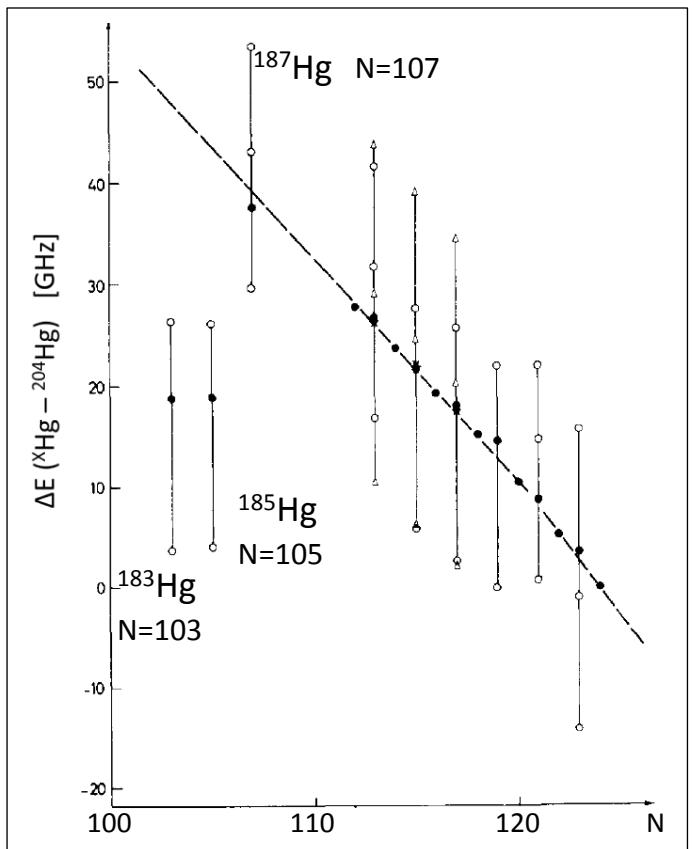


BMF predict different signs of the quadrupole moments compared to the experimental ones.

Shape coexistence in the lead region:

Sharp change transition in the ground state (^{187}Hg - ^{185}Hg):
from **weakly oblate** to **more prolate** deformed

J. Bonn et al., Phys.Lett. B38, 308 (1972)

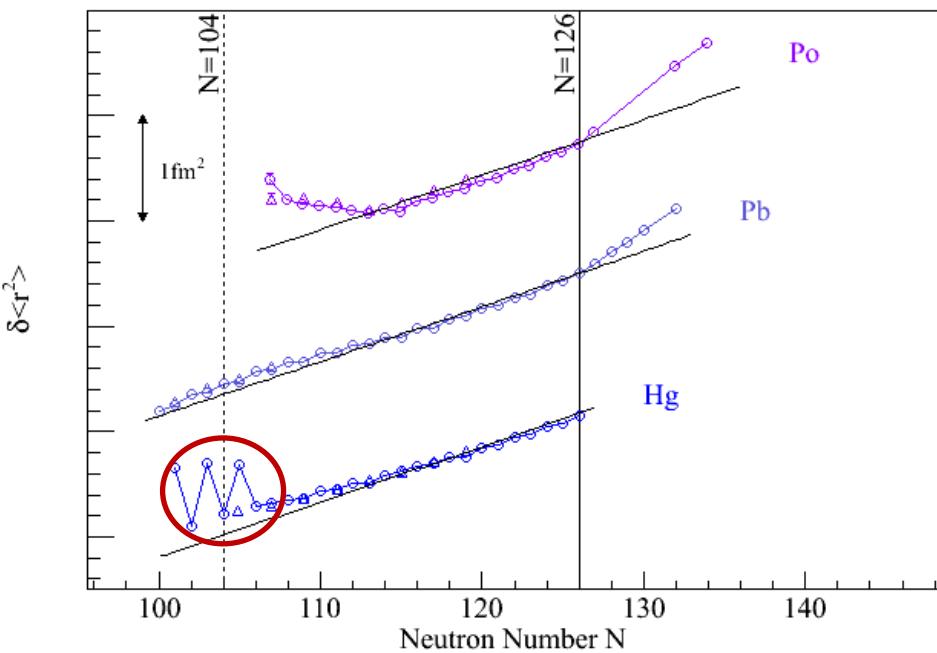


A. Andreyev et al., Nature 405, 430 (2000)

Significant deviation from sphericity deduced around N=104:

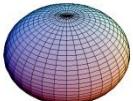
T.E. Cocolios et al. PRL 106 (2011) 052503

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

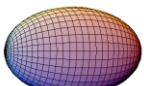


Shape coexistence in the light Hg isotopes (1)

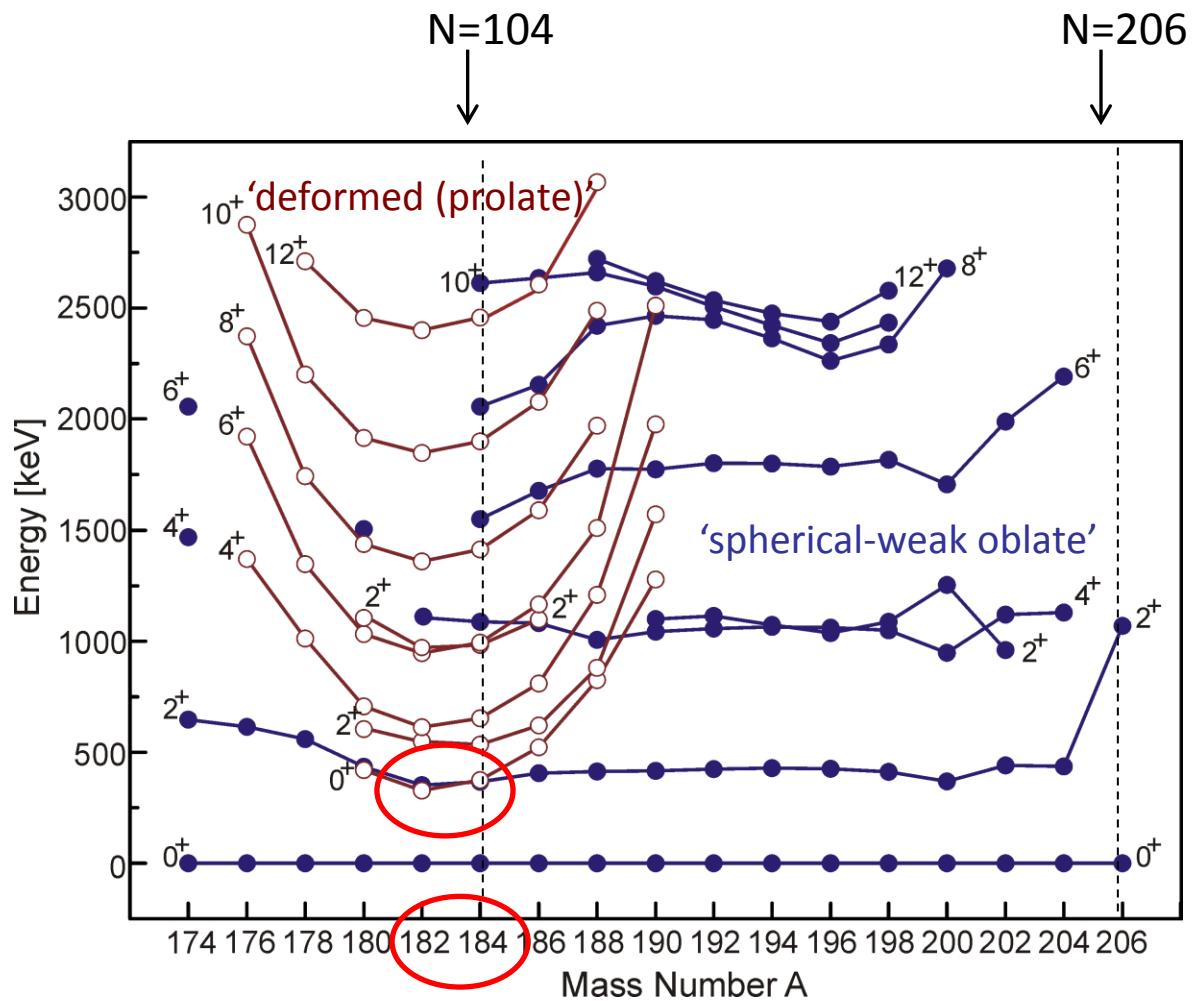
weakly oblate
ground state band



excited prolate
band



Systematic of the energy levels –
flat behaviour of the weakly oblate
states against parabolic behaviour of
the deformed states with a **minimum**
at mid-shell N = 104.



$^{182,184}\text{Hg}$ -> pronounced **mixing** between low lying excited states

Shape coexistence in the light Hg isotopes (2)

1089

4⁺

930

613
549

4⁺
2⁺

352

328

2⁺
0⁺

367

2⁺
0⁺

653
534

4⁺

2⁺

375

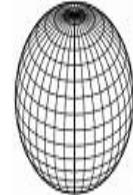
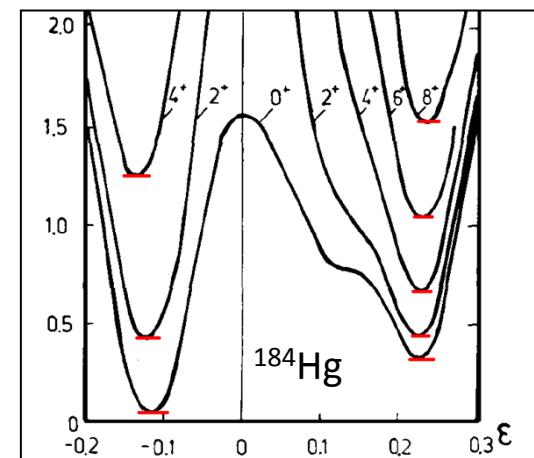
0⁺

0⁺

¹⁸²Hg

¹⁸⁴Hg

S. Frauendorf & V. V. Paskevich Phys.Lett. B 55 (1975) 365
W. Nazarewicz et al. Phys.Lett.B 305 (1993) 195



Ground state band: slightly oblate (2h)

deformation $\beta_2 \approx -0.15$

Excited band: prolate (4p-6h)

deformation $\beta_2 \approx +0.25$

- Strong mixing in the low-energy part of the level scheme
- ‘oblate’ – ‘prolate’: model dependent interpretation
- Coulomb excitation