Shape coexistence in gold, mercury and bismuth isotopes studied by insource laser spectroscopy at RILIS-ISOLDE

Andrei Andreyev
University of York(UK), JAEA(Tokai, Japan), CERN-ISOLDE
on behalf of RILIS-Windmill-ISOLTRAP collaboration

- **Reminder on shape coexistence in the lead region**
- **Isotope Shift(IS) and Hyperfine Splitting (HFS) measurements**
- **ISOLDE and our detection tools**
- **Hg chain – is there life after staggering?**
- **Au chain – back to sphericity**
- **Bi chain – following the steps of Hg's?**

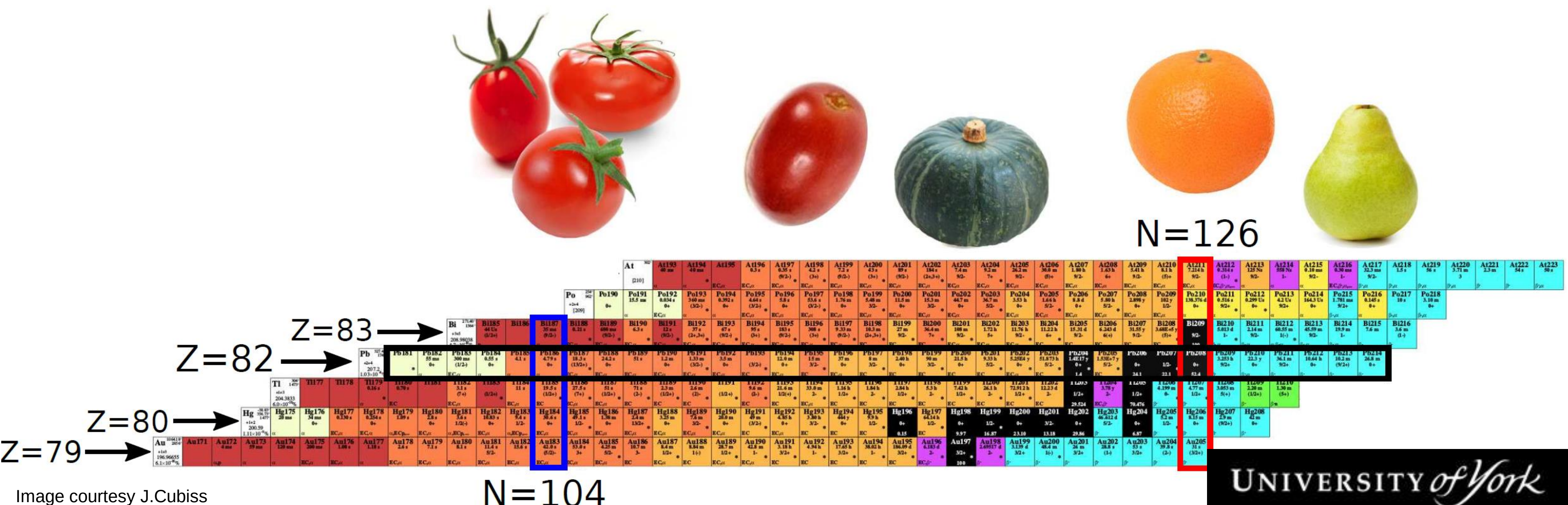

Image courtesy J.Cubiss

Windmill-ISOLTRAP-IDS-RILIS Collaboration '2018

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  S. Sels, L. Ghys, C. Van Beveren, Yu. Kudryavtsev, M. Huyse, P. Van Duppen, L. Gaffney, T. E. Cocolios,, G. J. Farooq-Smith
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  A. Barzakh, D. V. Fedorov, P. Molkanov, M.D. Seliverstov
- **University of Manchester, UK**

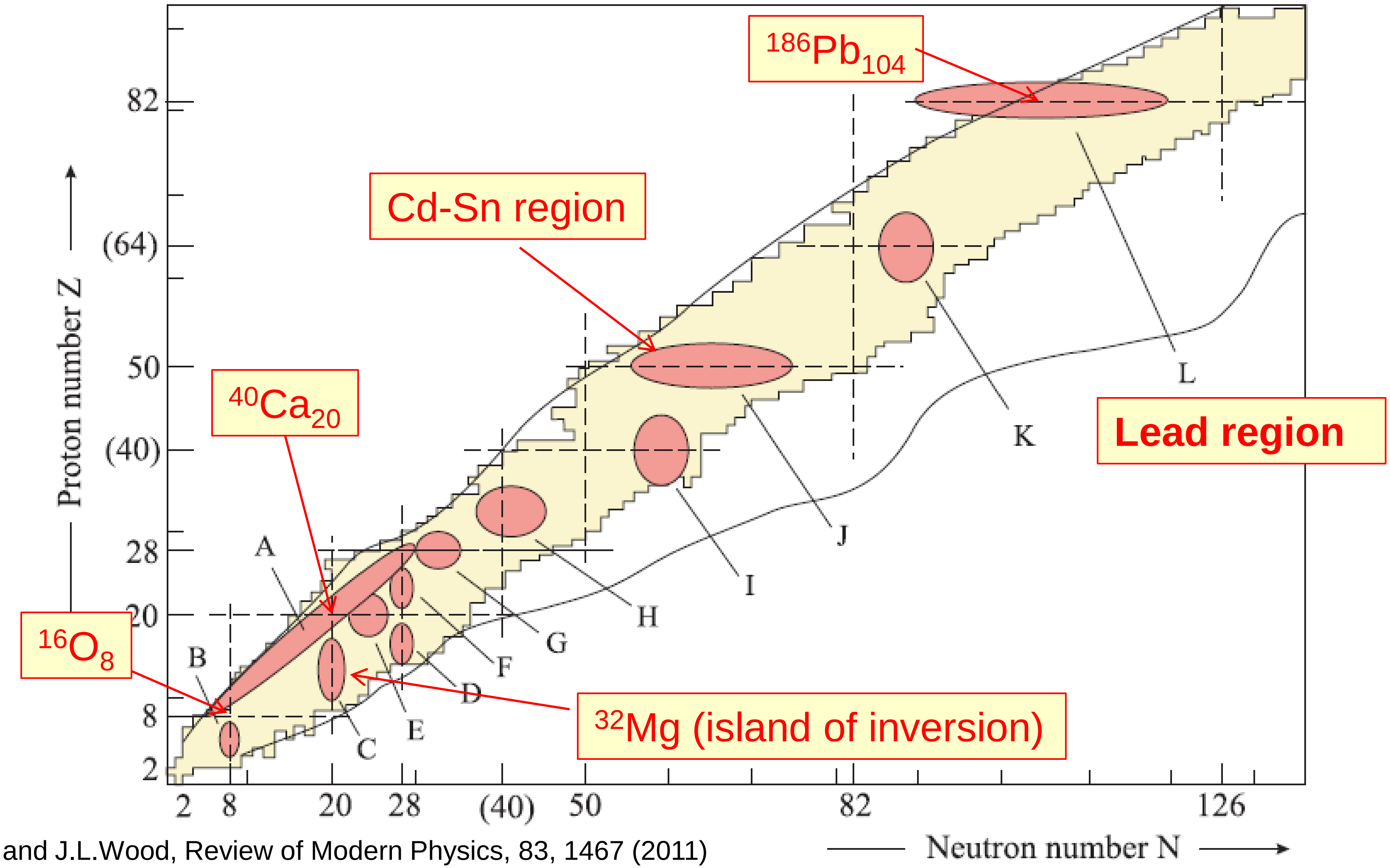
  J. Billowes, M. Bissel
- **MR-TOF@ISOLTRAP team**

  S. Kreim, V. Manea, F. Wienholtz +...

- Highly collaborative
- 15 institutions, >40 atomic and nuclear physicists
- Many PhD students, both atomic and nuclear physics

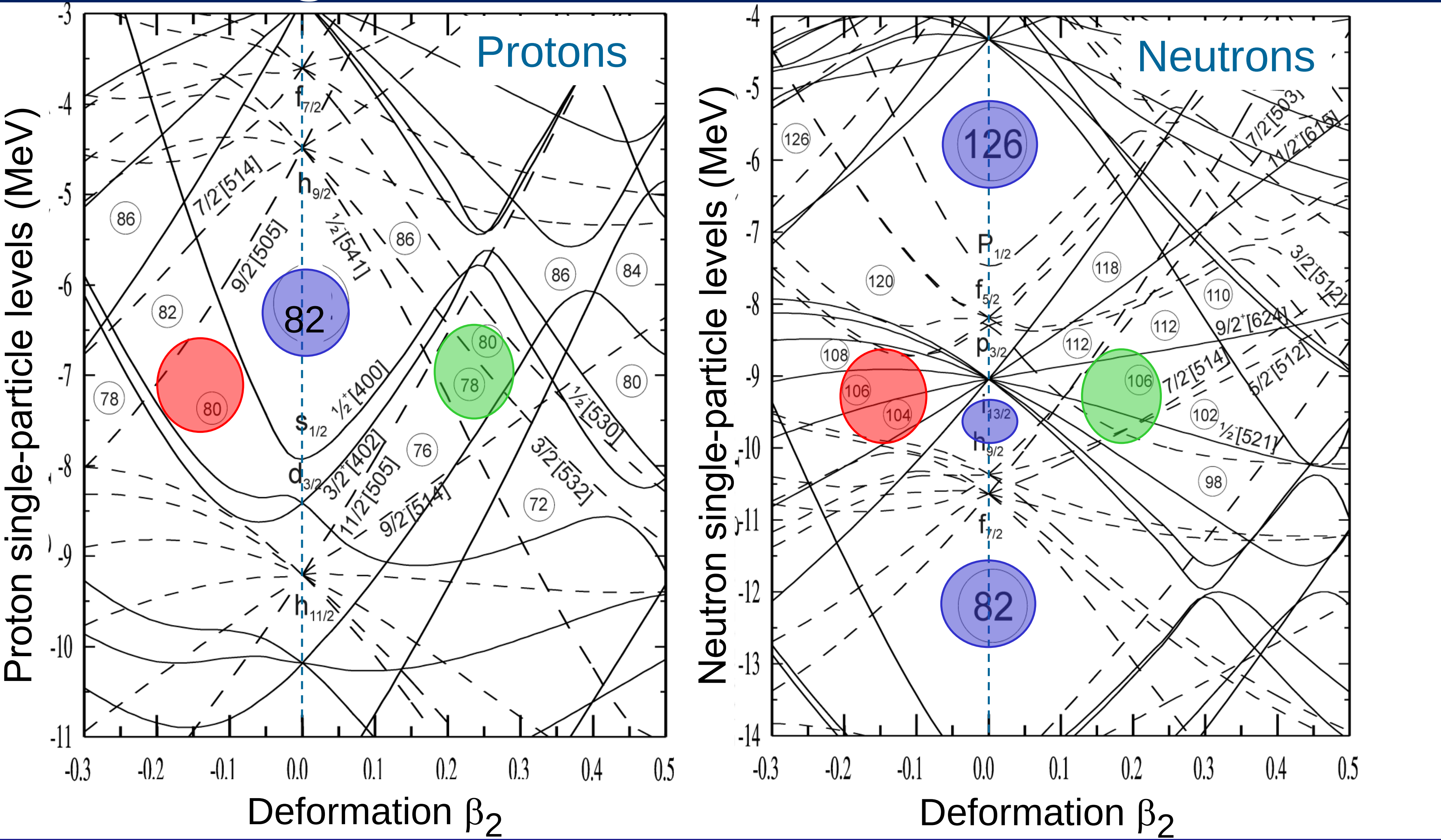
Shape coexistence around closed proton and/or neutron shells (and subshells)

- spherical and deformed structures co-exist in the nucleus at low energy
- its study can contribute in finding a unified description for atomic nuclei
- supplies information about the mixing between these configurations

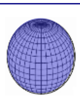
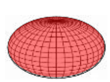
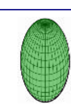


K. Heyde and J.L.Wood, Review of Modern Physics, 83, 1467 (2011)

Nilsson Diagrams around Z~82 & 82<N<126 (WS)

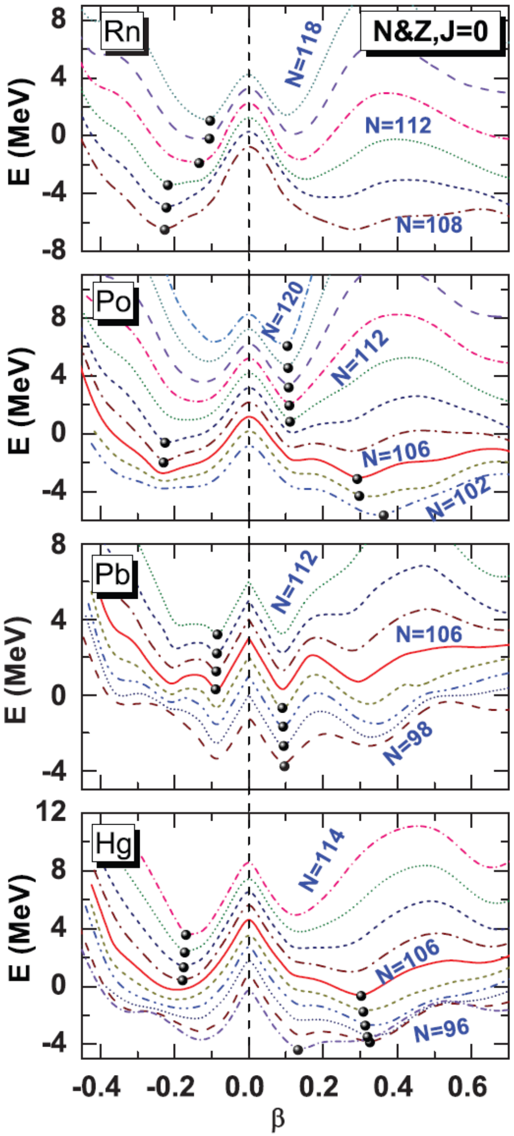


Around Z=82 and neutron mid-shell N=102-108, protons and neutrons coherently produce low-lying coexisting oblate and prolate shapes


Spherical

Oblate

Prolate

(An example) Modern 'state-of-the art' beyond mean-field calculations (SLy6+GCM)

J.M.Yao, M. Bender, P.-H. Heenen, PRC87,034322(2013)



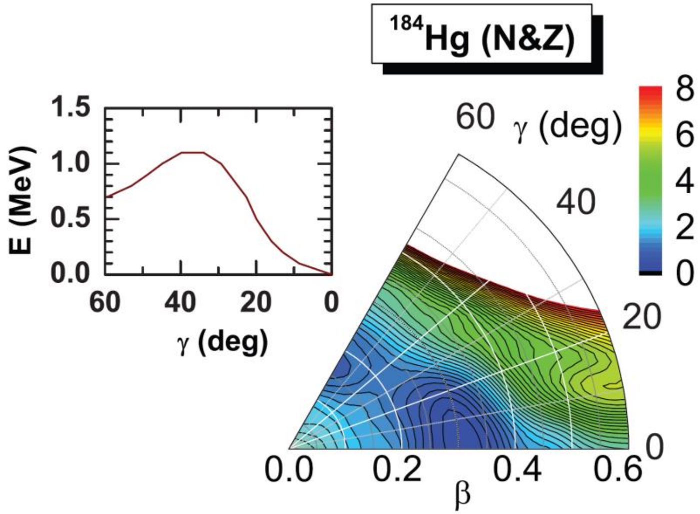


FIG. 4. (Color online) Quadrupole deformation energy surface for ^{184}Hg, normalized to the absolute minimum and projected on particle numbers. Each contour line is separated by 0.2 MeV. The inset shows the energy as a function of γ deformation along the path joining the two axial minima.

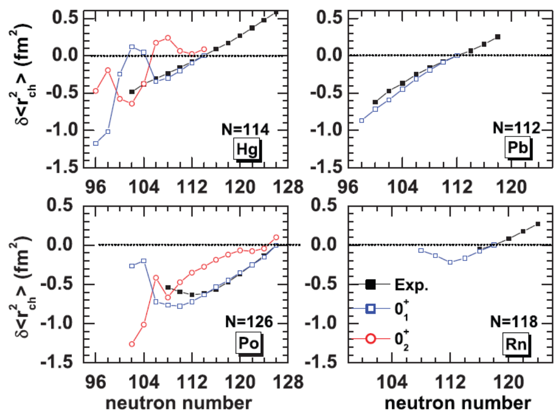
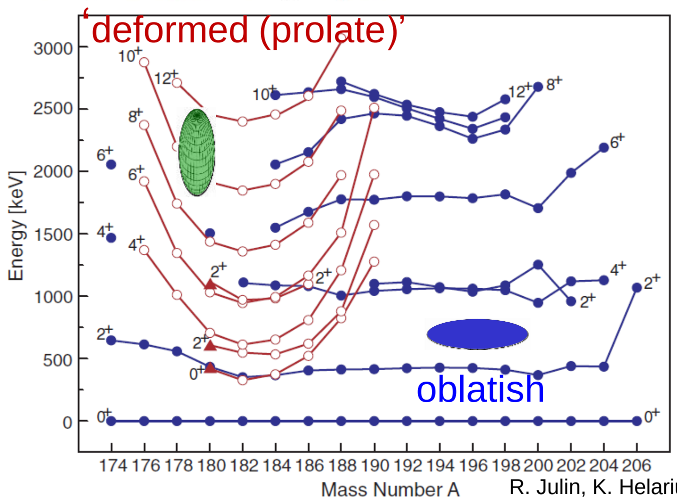


FIG. 13. (Color online) (Upper panel) Variation of the charge radii $\delta\langle r_{ch}^2\rangle$ for the lowest 0^+ states in Hg [normalized to the ground state (g.s.) of ^{194}Hg], Pb (normalized to the g.s. of ^{194}Pb), Po (normalized to the g.s. of ^{210}Po), and Rn (normalized to the g.s. of ^{204}Rn) isotopes, compared to the the experimental data for ground states taken from Refs. [18,49].

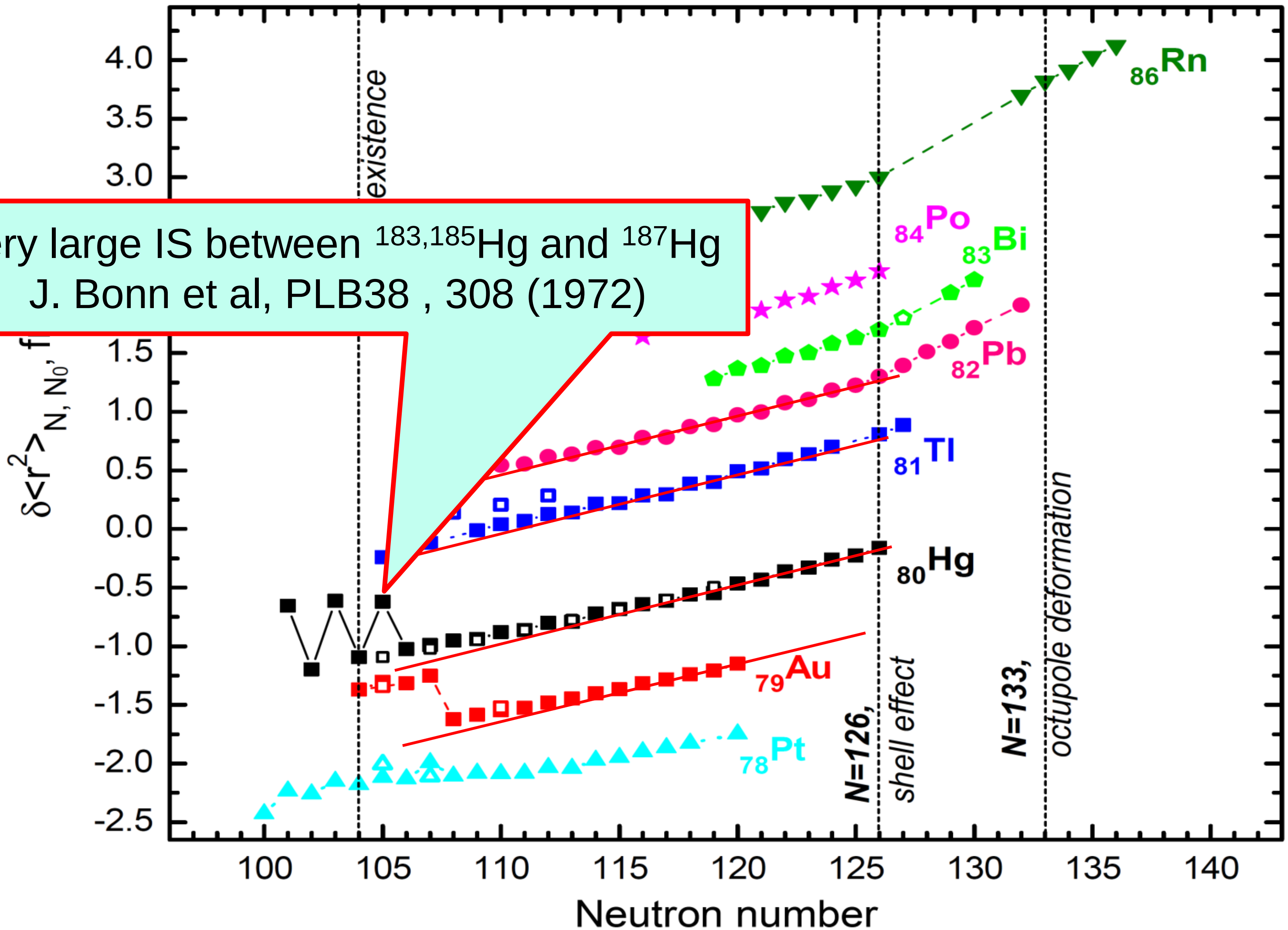


R. Julin, K. Helariutta, M. Muikku, J. Phys. G 27 (2001)

Studies in the Lead Region

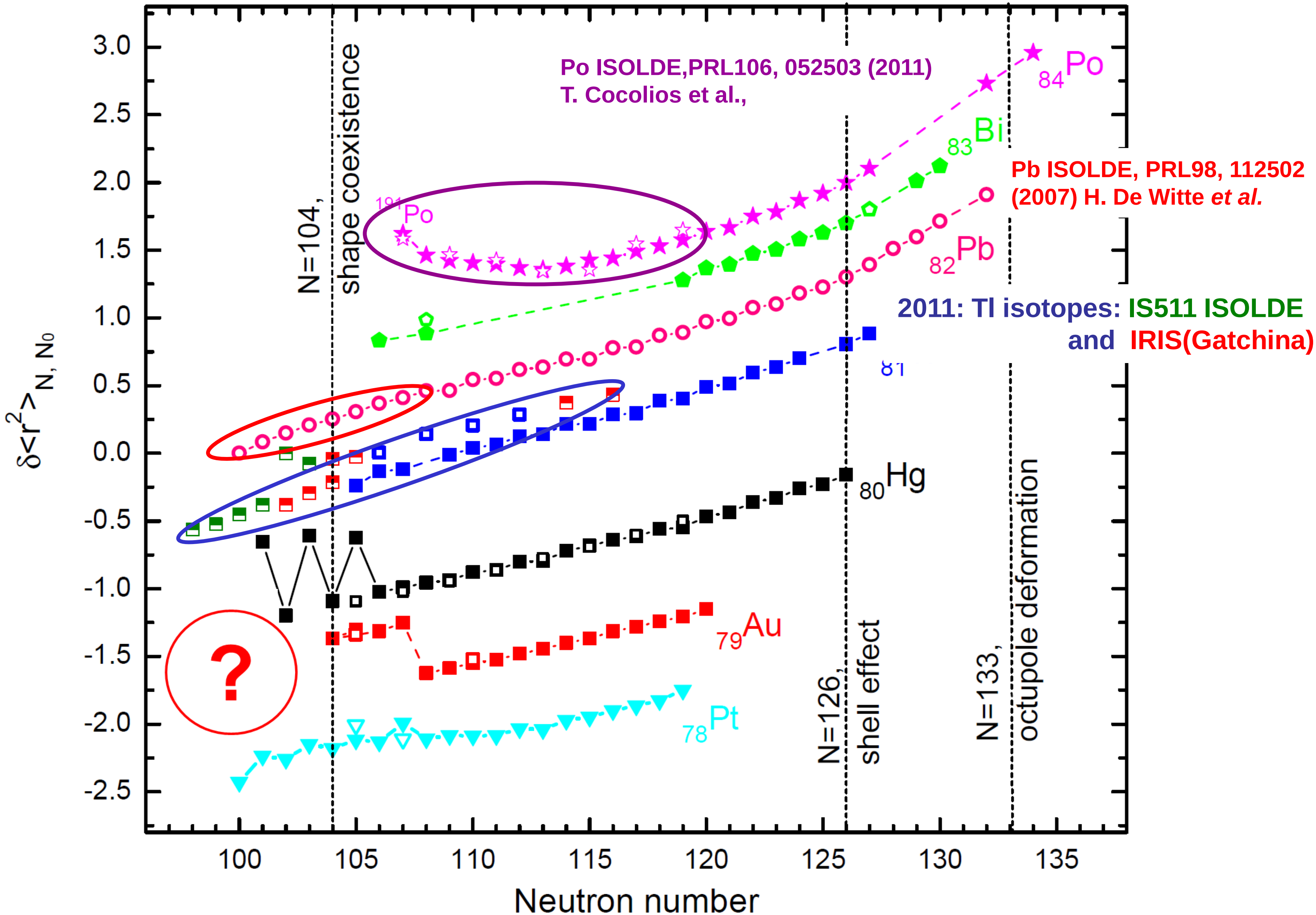
- Particle decay studies (alpha/beta,E0’s)
- In-beam γ-ray studies (RDT/IDT), isomeric states
- Plunger/lifetimes
- Coulex
- Moments
- **Optical/Laser spectroscopy: Hyperfine splitting, isotope shift (HFS/IS)**
- …

Pre-2003: Charge Radii in the Lead Region

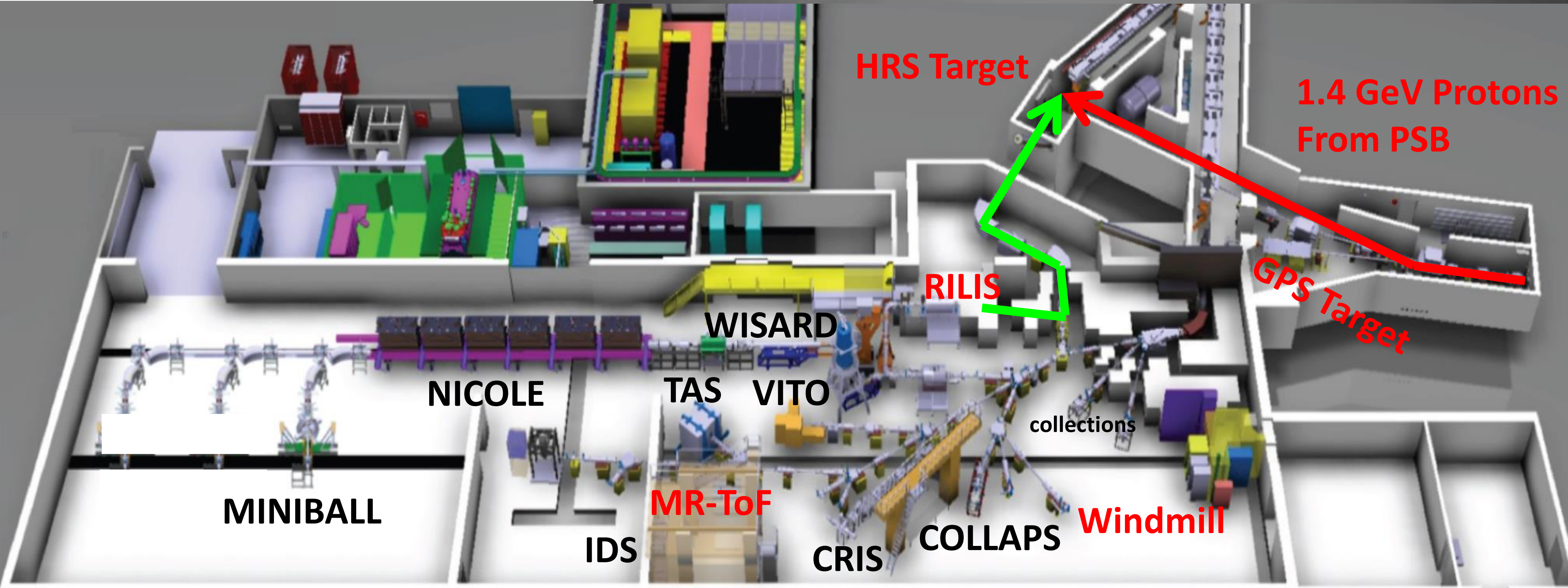


- Shape coexistence around N~104
- Sphericity around N=126, kink in radii, high-spin isomers
- Octupole effects around N~132, inverse odd-even radii staggering

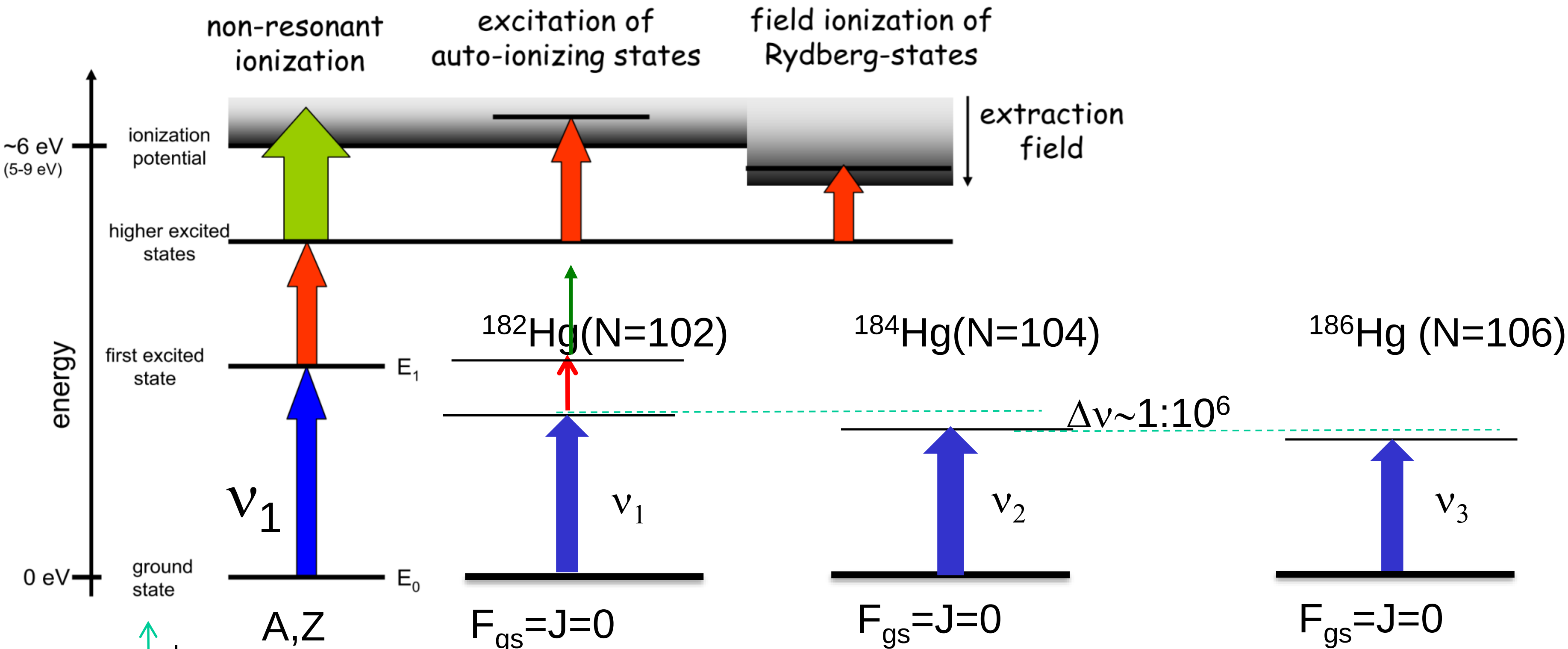
2003-2011: Charge Radii in the Lead Region

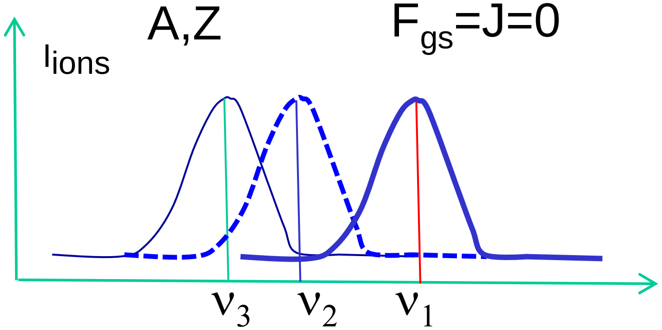


The ISOLDE facility at CERN



Resonance Laser Spectroscopy of an Atom





•$\Delta\nu=\nu_1-\nu_2$ Isotope Shift (IS) or HFS

IS/HFS proportional to the charge radius

$$\delta\nu^{A,A'} = \underbrace{M_i \frac{A'-A}{AA'}}_{\text{Mass shift}} + \underbrace{F_i\, \delta\langle r^2\rangle^{A,A'}}_{\text{Field shift}}$$

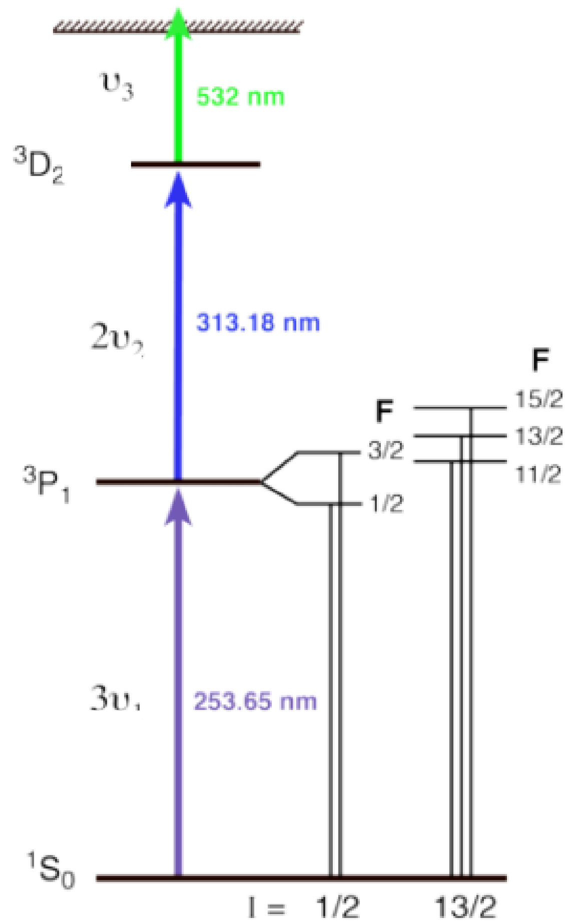
•**Scanning the laser frequency of the resonance step**

•**Measuring α/γ or ToF spectra while scanning the frequency**

Resonance Laser Spectroscopy of an Atom

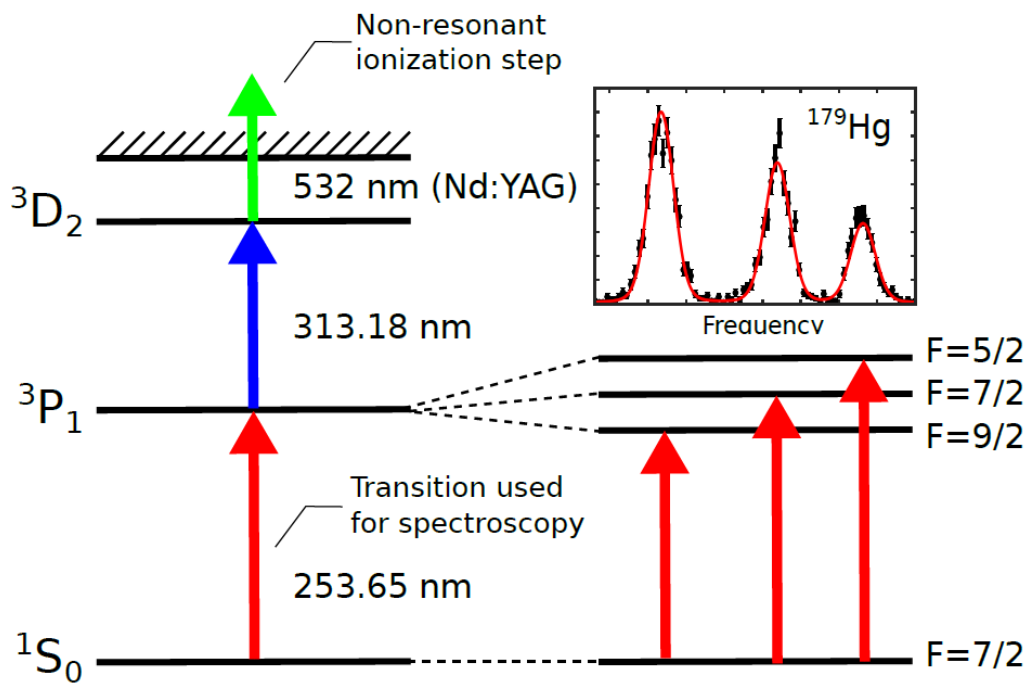
$$F_{atom} = I_{nuclear} + J_{electron}$$

$$\Delta F = 0, \pm 1$$



- More complex in odd-A (odd-odd-A) cases
- Needs to consider HFS splitting (see examples further in the talk)

e.g. for I=7/2 in ^{179}Hg

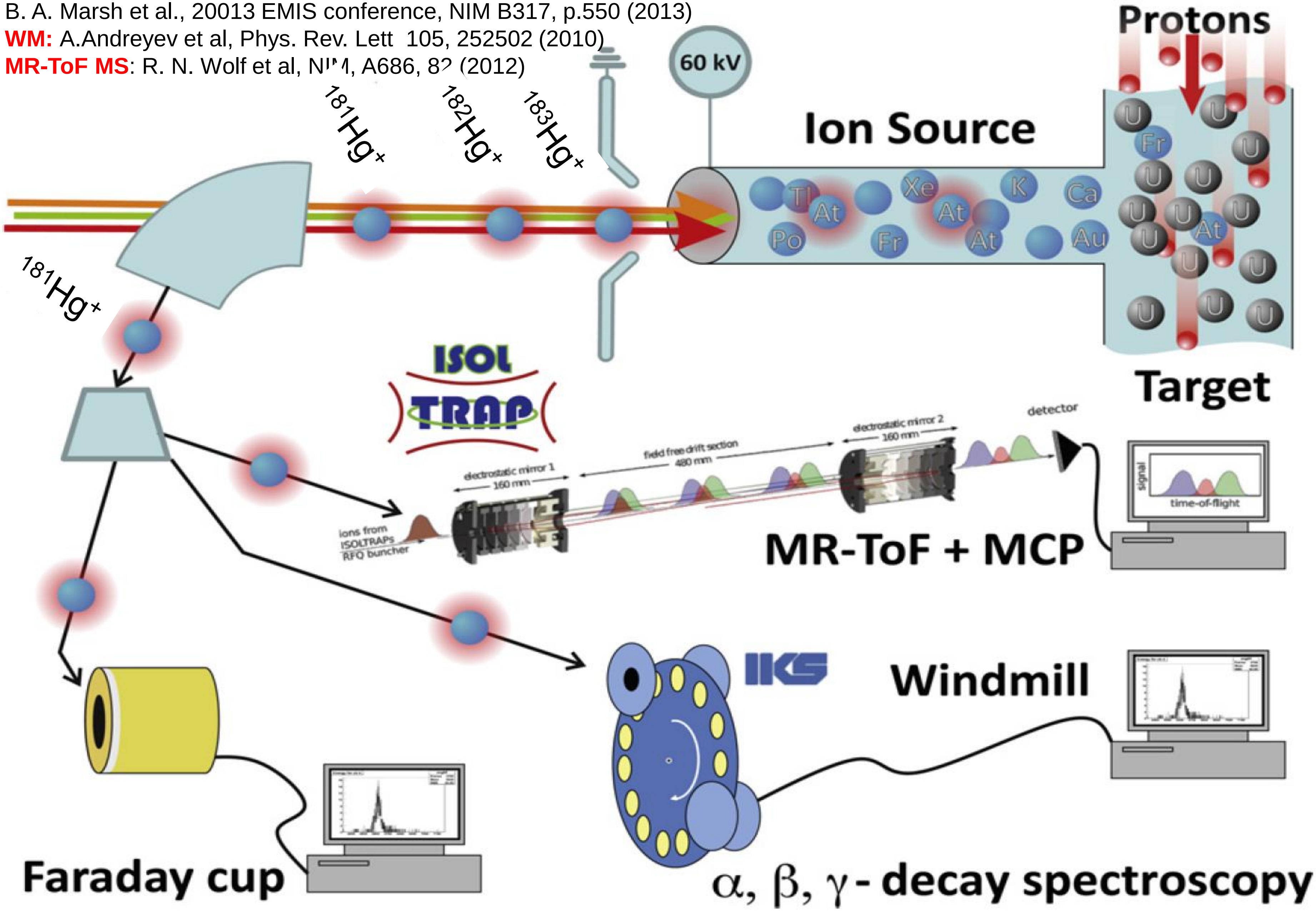


Our tools '2018 WindMill (WM), FC, MR-TOF MS

B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)

WM: A.Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)

MR-ToF MS: R. N. Wolf et al, NIM, A686, 82 (2012)



Hg with VADLIS@ISOLDE from Molten Lead Target

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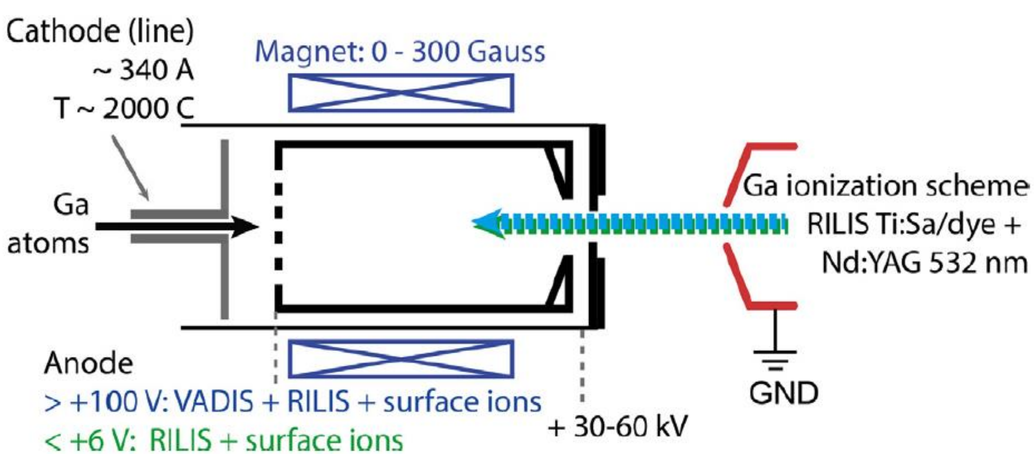
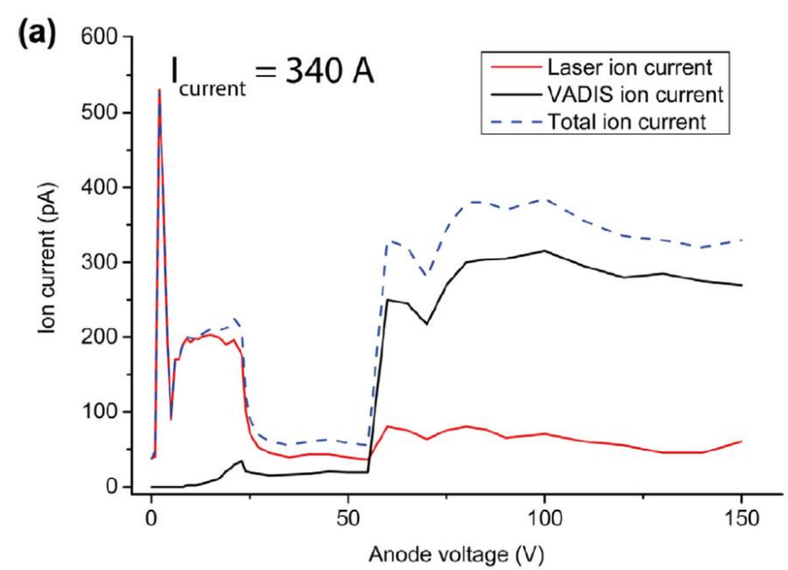
journal homepage: www.elsevier.com/locate/nimb

Blurring the boundaries between ion sources: The application of the RILIS inside a FEBIAD type ion source at ISOLDE

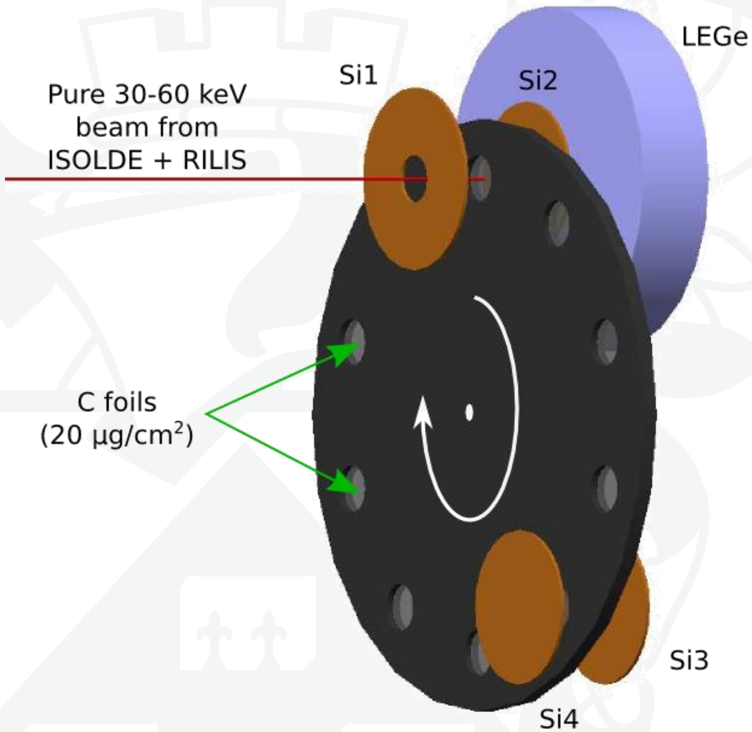
T. Day Goodacre [a,b,*], J. Billowes [b], R. Catherall [a], T.E. Cocolios [b], B. Crepieux [a], D.V. Fedorov [c], V.N. Fedosseev [a], L.P. Gaffney [e,1], T. Giles [a], A. Gottberg [a], K.M. Lynch [a], B.A. Marsh [a], T.M. Mendonça [a], J.P. Ramos [a,d], R.E. Rossel [a,f,g], S. Rothe [a], S. Sels [e], C. Sotty [e], T. Stora [a], C. Van Beveren [e], M. Veinhard [a]

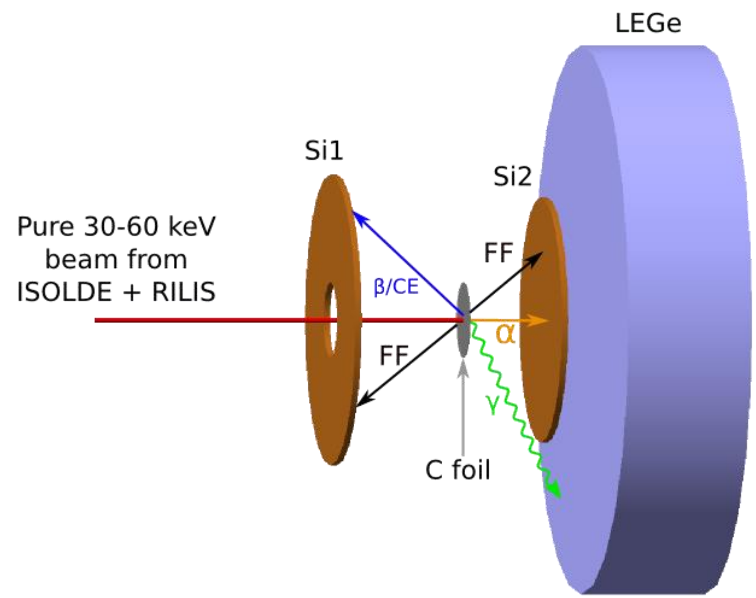




Windmill Detection System

A. Andreyev et al., PRL 105, 252502 (2010)



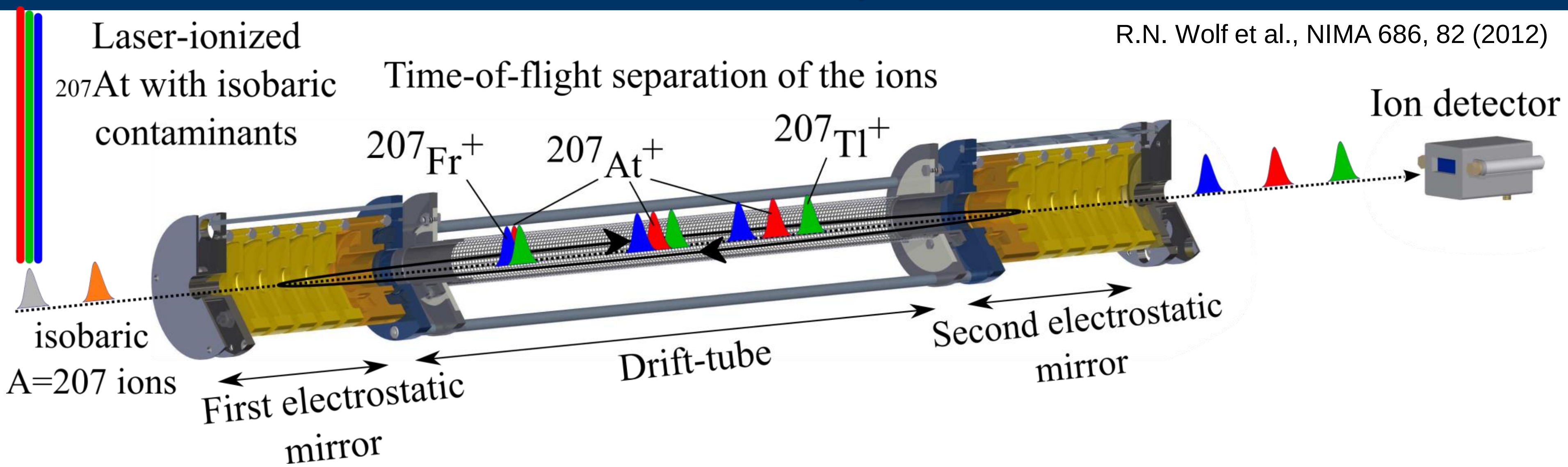


Setup: Si detectors both sides of the C-foil

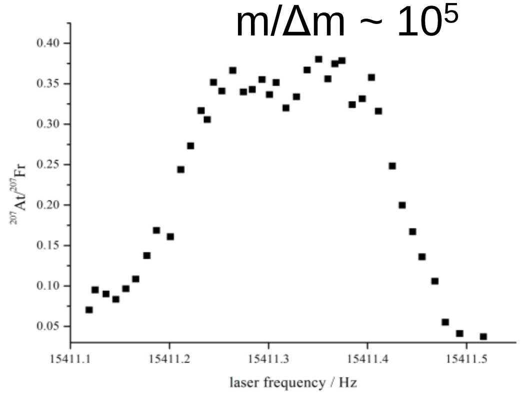
- Simple setup & DAQ: 2 Surface barrier detectors (1 of them – annular) and 2 PIPS detectors.
- 34% geometrical efficiency at implantation site.
- Alpha-gamma coincidences
- Digital electronics

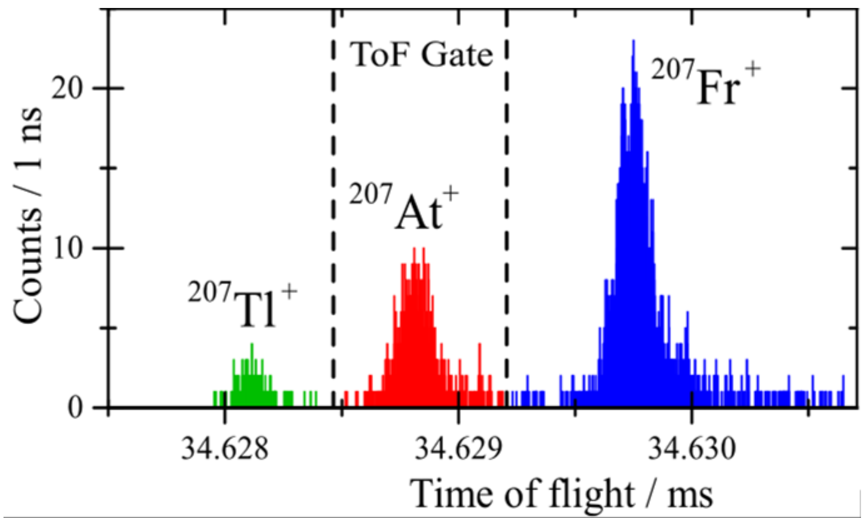
MR-ToF Mass Spectrometer

R.N. Wolf et al., NIMA 686, 82 (2012)



~1000 revolutions, ~35 ms,
m/Δm ~ 10^5

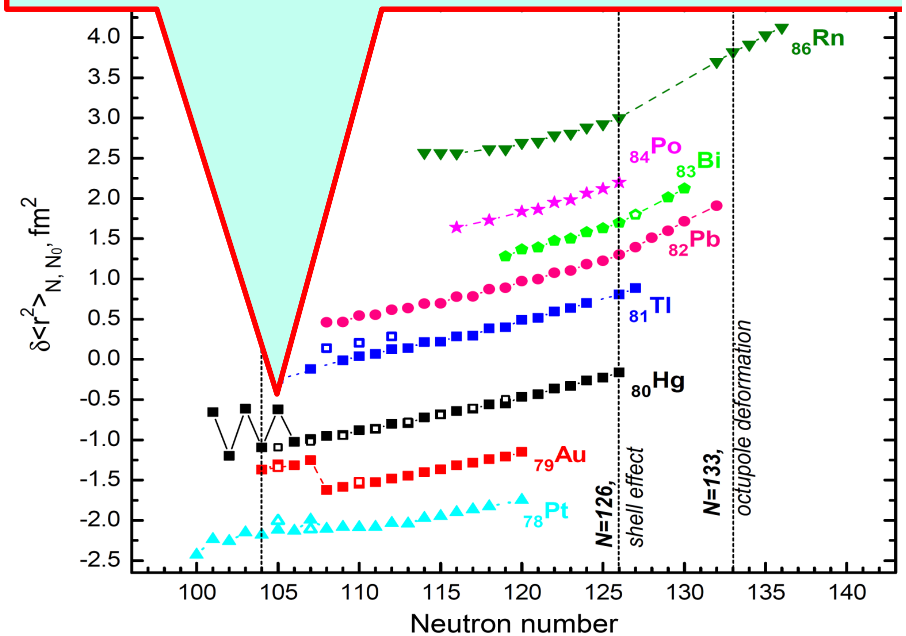




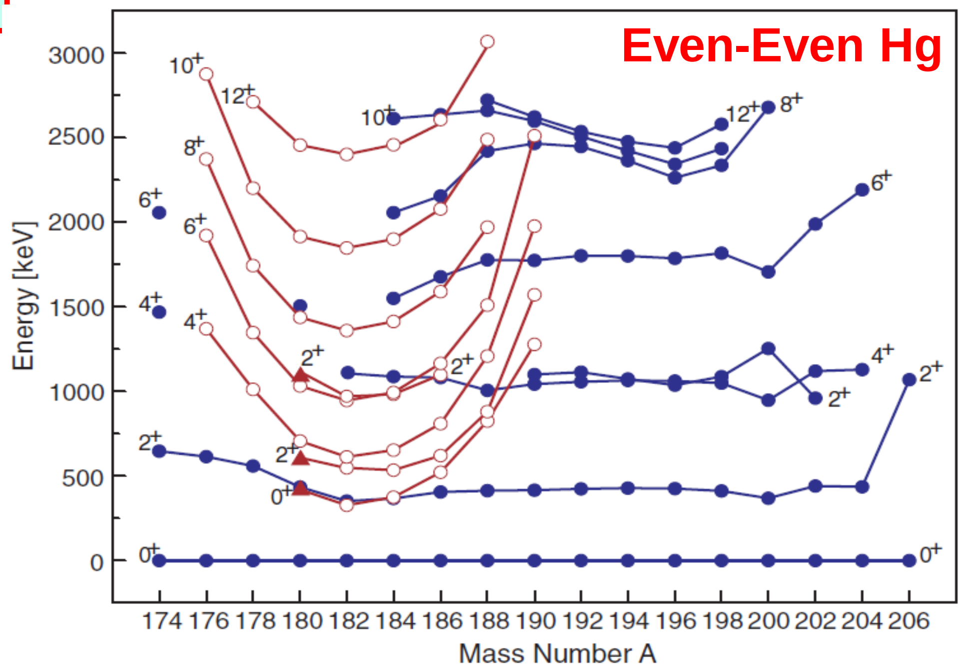
- MR-ToF MS counts ions, thus is not limited by decay scheme or long half-lives
- MR-ToF MS offers a way to separate background for direct single-ion detection using MCP (time scale: tens of ms).

April 2015: IS598@ISOLDE – Hg isotopes (or, what happens after shape staggering in $^{181-185}$Hg?)

Large IS between ^{183,185}Hg and ^{187}Hg
J. Bonn et al, PLB38, 308 (1972)



R. Julin, K. Helariutta, M. Muikku, J. Phys. G 27 (2001)

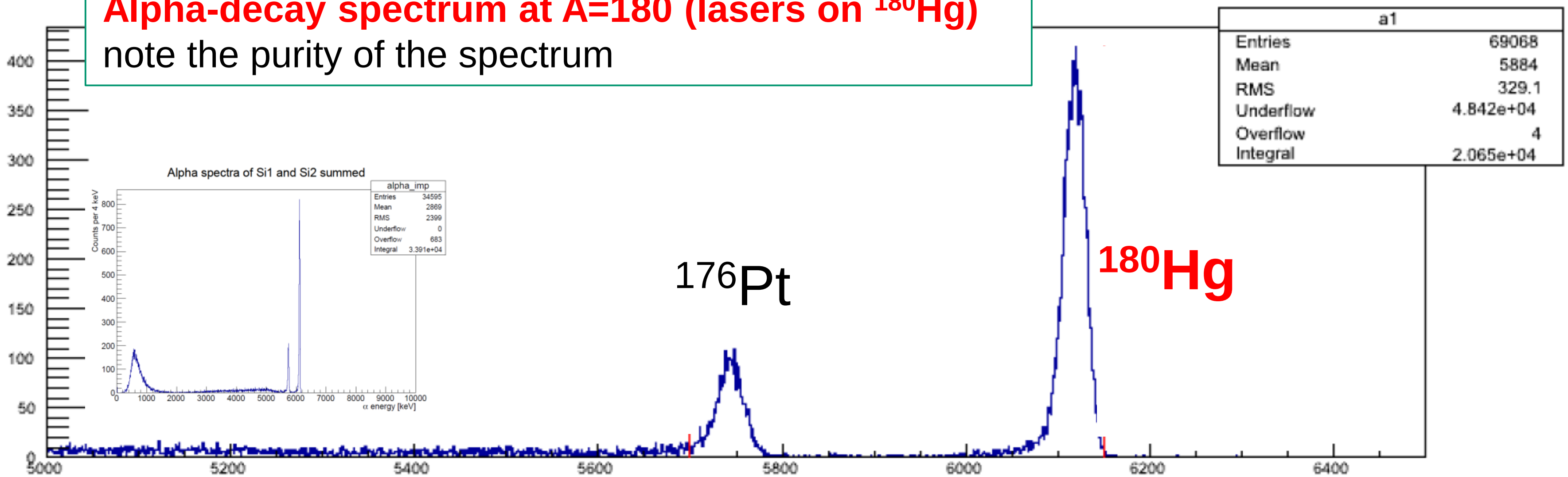


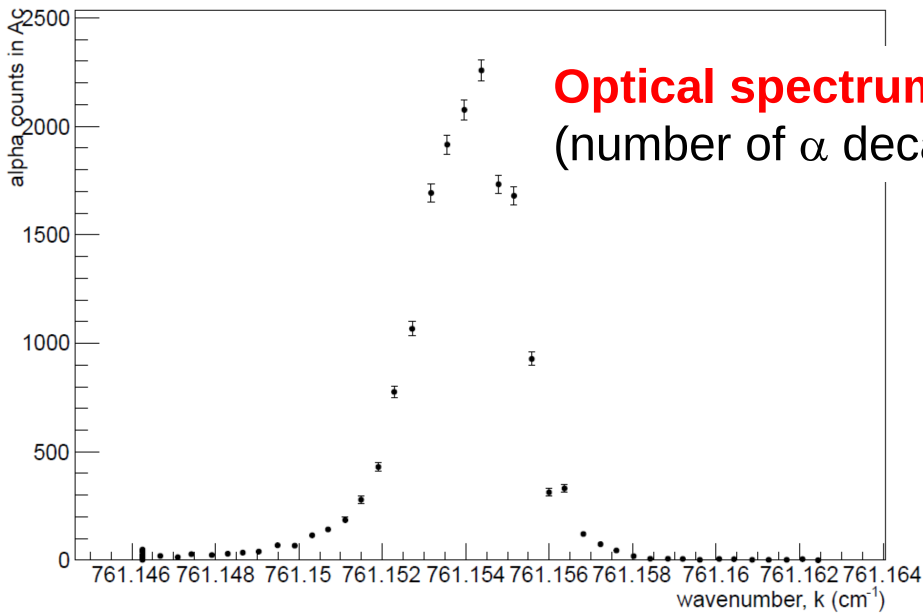
Previous Hg radii data (ISOLDE)
^{183,185,187,199,201}Hg: J. Bonn et al, PLB38, 308 (1972)
$^{181-191}$Hg: J. Bonn et al., ZPhys A 276, 203 (1976)
$^{182-198}$Hg: G. Ulm Z. Phys. A 325, 247 259 (1986)
Note: gs of ^{182,184,186}Hg – weakly oblate

In-beam Hg data - examples (RDT, plunger, Coulex)
^{184,186}Hg; L.P. Gaffney LP *et al.* PRC89 024307(2014)
^{172}Hg: M. Sandzelius et al, PRC79, 064315 (2009)
^{175}Hg: D. O'Donnell et al., PRC79, 051304(2009)
^{176,178}Hg: M. P. Carpenter et al, PRL78, 3650(1997)
^{176}Hg: M. Muikku et al, PRC58, 3033 (1998)
^{180,182}Hg: T. Grahn et al, PRC80, 014324 (2009)

^{180}Hg@Windmill

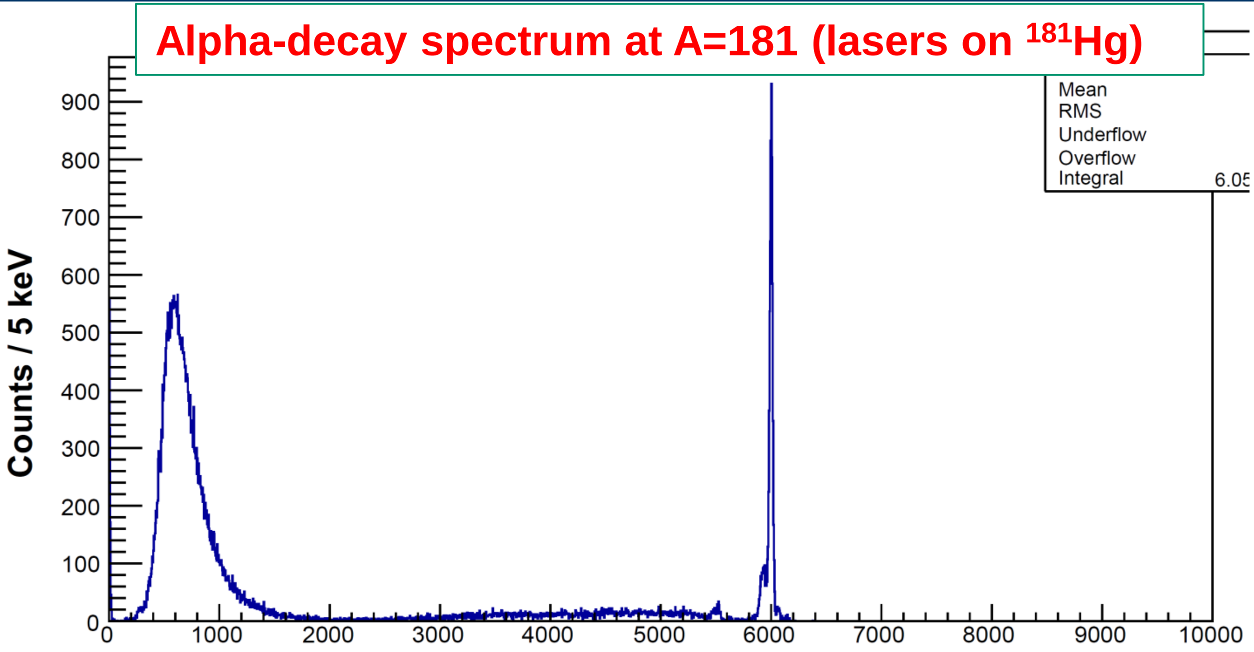
Alpha-decay spectrum at A=180 (lasers on ^{180}Hg)
note the purity of the spectrum

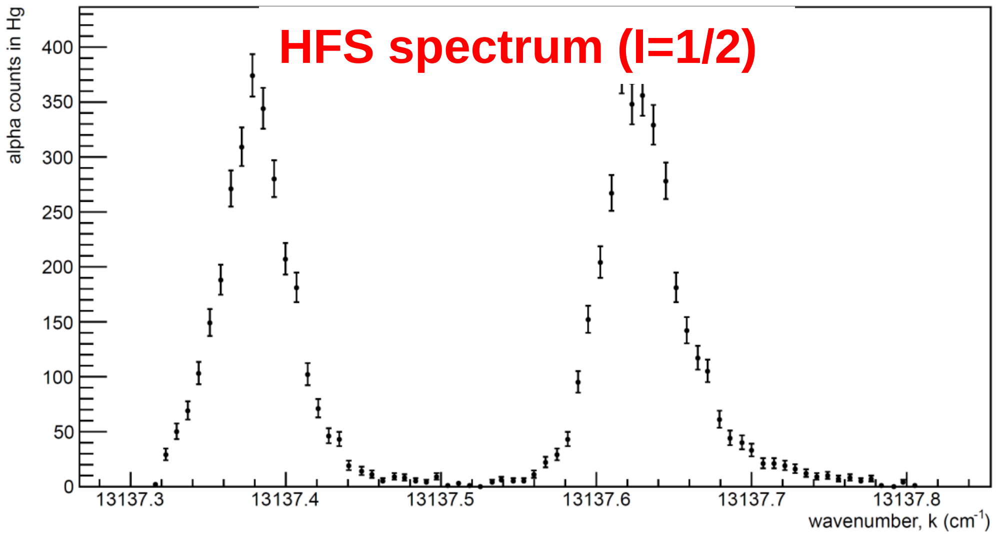




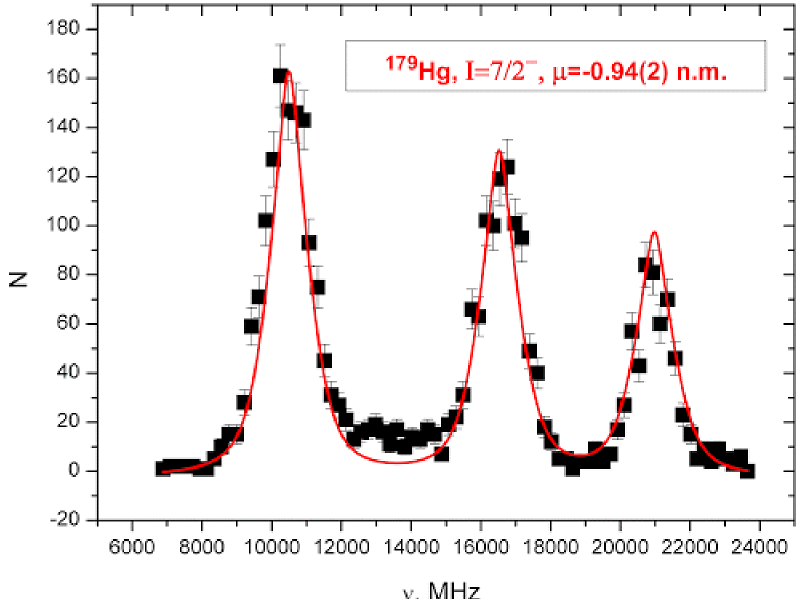
Optical spectrum (even-even case, I=0^+)
(number of α decays as a function of laser frequency)

^{181}Hg@Windmill

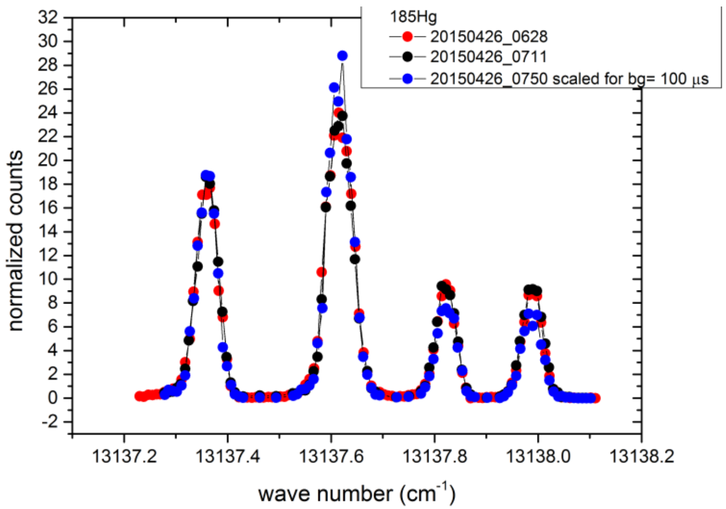




$^{179,185,207,208}Hg$



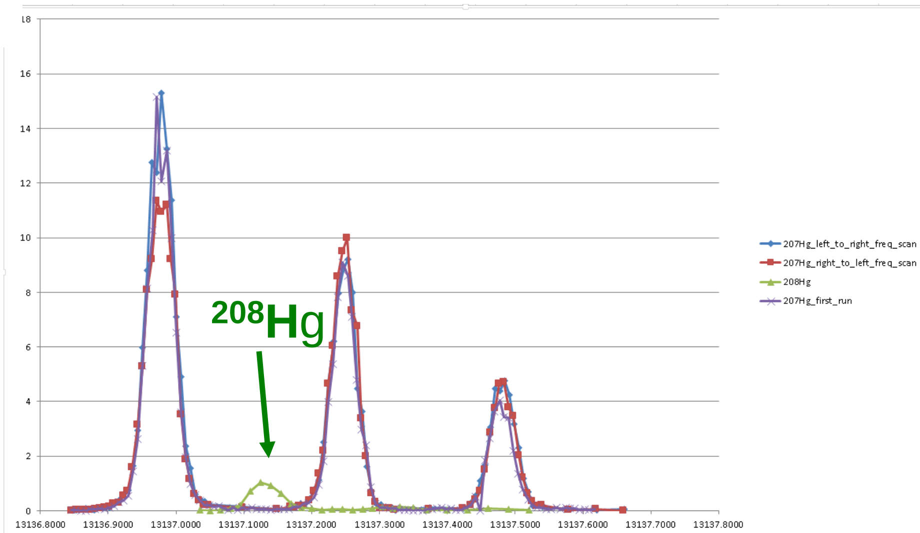
^{185}Hg HFS spectrum@MR-ToF, gs+is



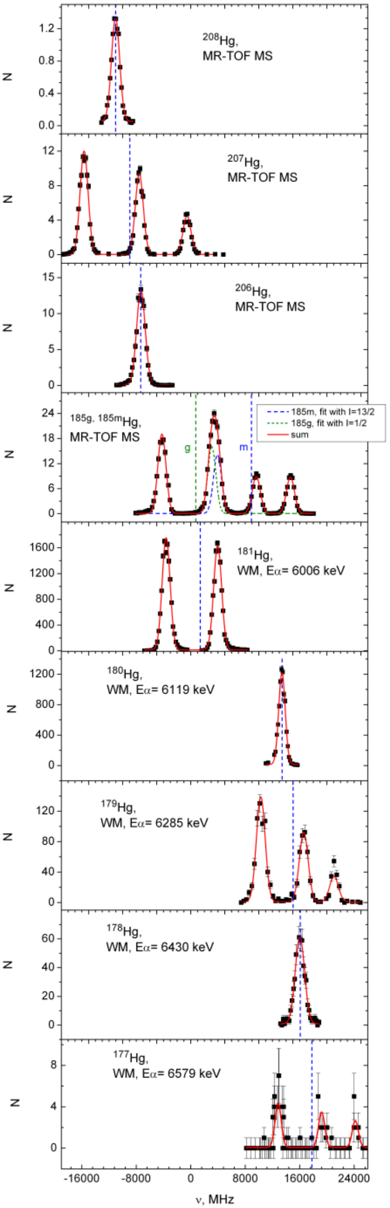
Isotopes with N>126

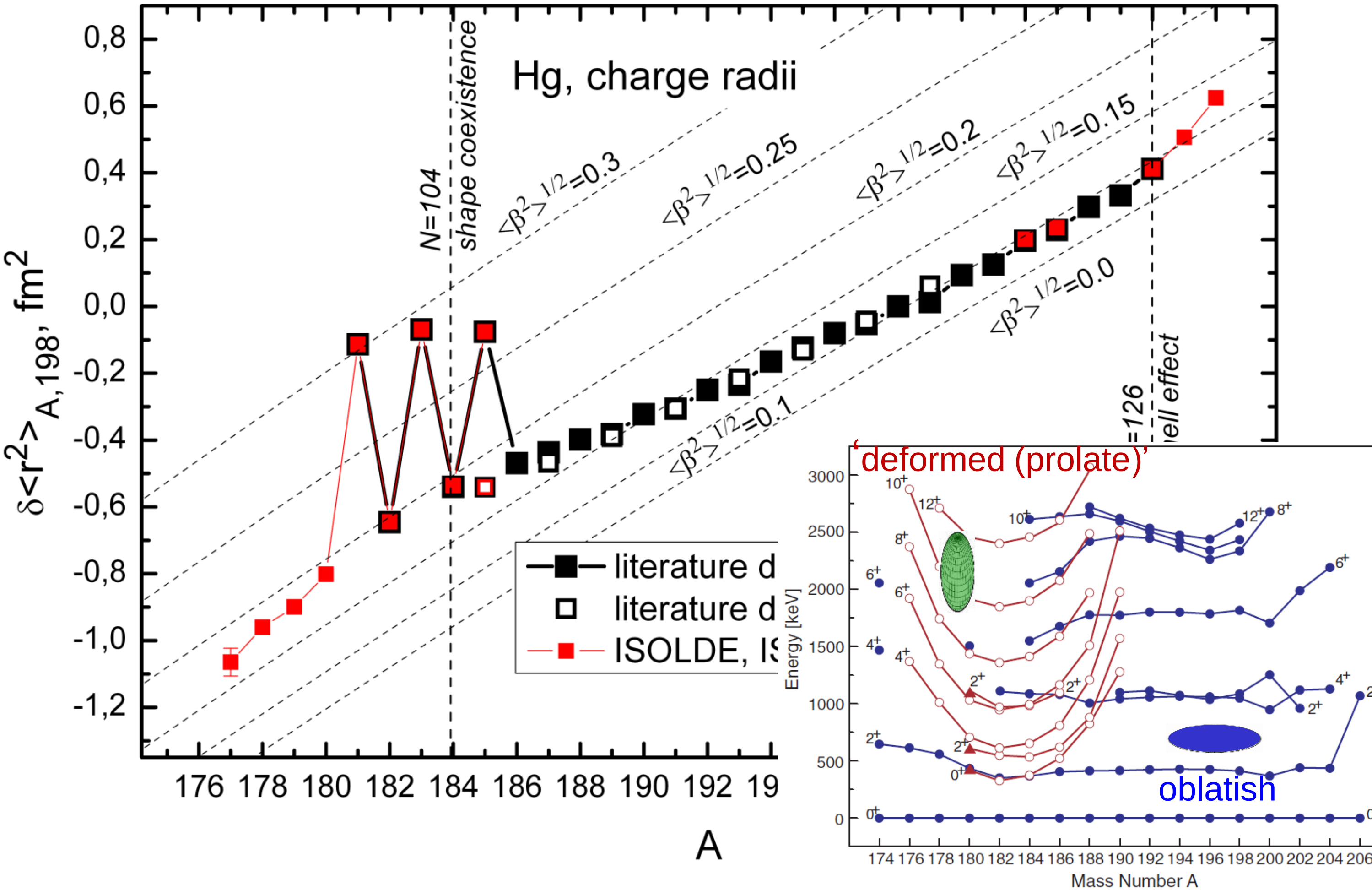
^{207}Hg HFS spectra@MR-ToF, I=9/2

also ^{208}Hg! I=0



HFS spectra and Charge radii for Hg isotopes



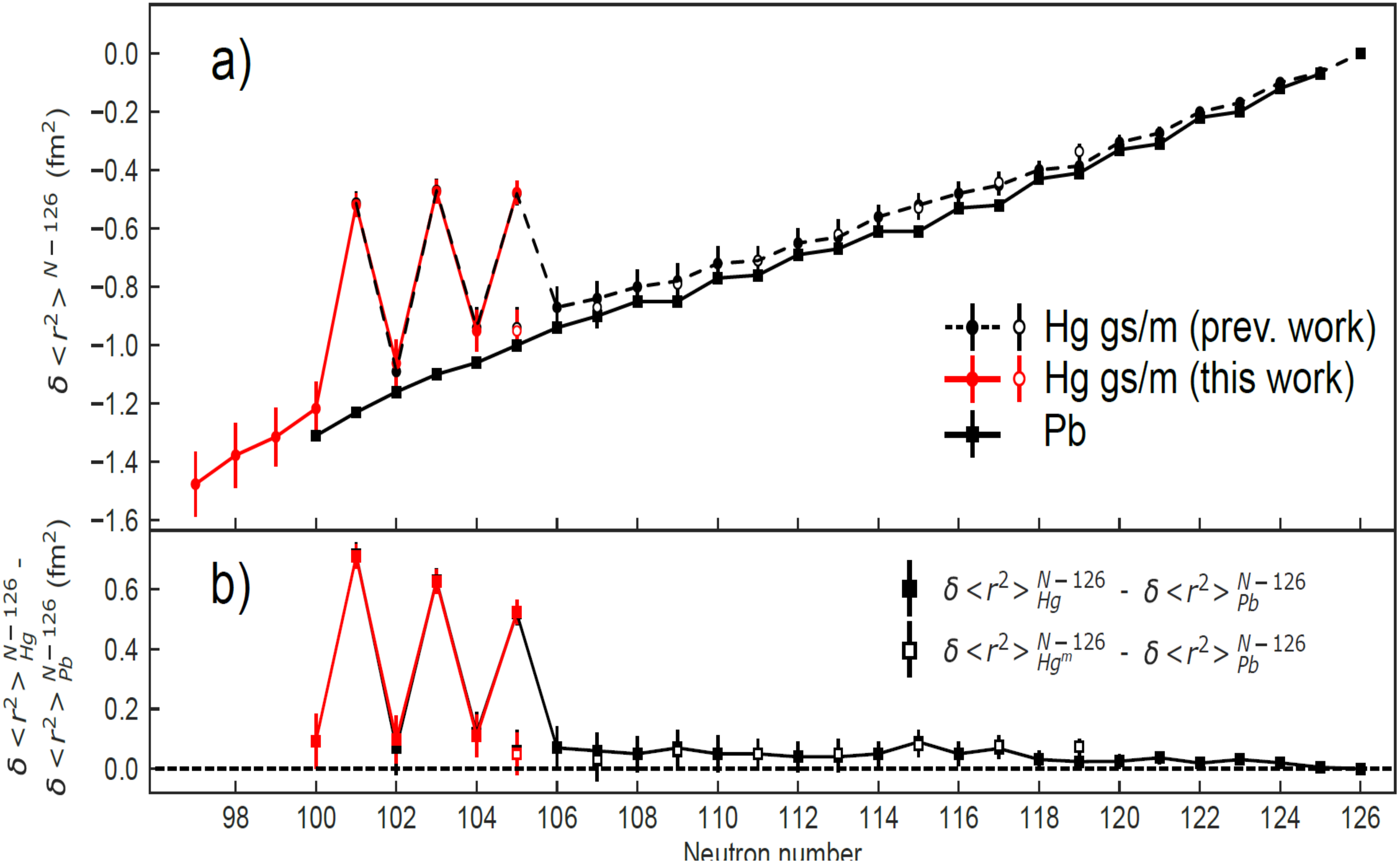


^{181,183,185}Hg- confirmation of earlier data on staggering for ½$^-$ gs

^{177,178,179,180}Hg (new) – trend towards sphericity

^{207,208}Hg (new): kink beyond N=126

Comparison Hg vs Pb chains



S.Sels et al, to be submitted to PRC, July 2018

Density Functional Theory (DTF) Calculations (York-Lyon-Brussels Collaboration)

- Extensive Density Functional Theory blocked calculations performed by the York-Lyon-Brussels Collaboration (14 parametrizations of Skyrme functionals were probed)

- UNEDF0, UNDEF1, UNDED1^{SO}, SLy4, SkM*, SGII
- 8 parametrizations of SLy5sX (different surface tension)

- Variation of pairing strength or surface tension

- Full account of calculations: S.Sels et al, to be submitted to PRC, July 2018

Some details of DFT calculations (changing pairing strenght or surface tension)

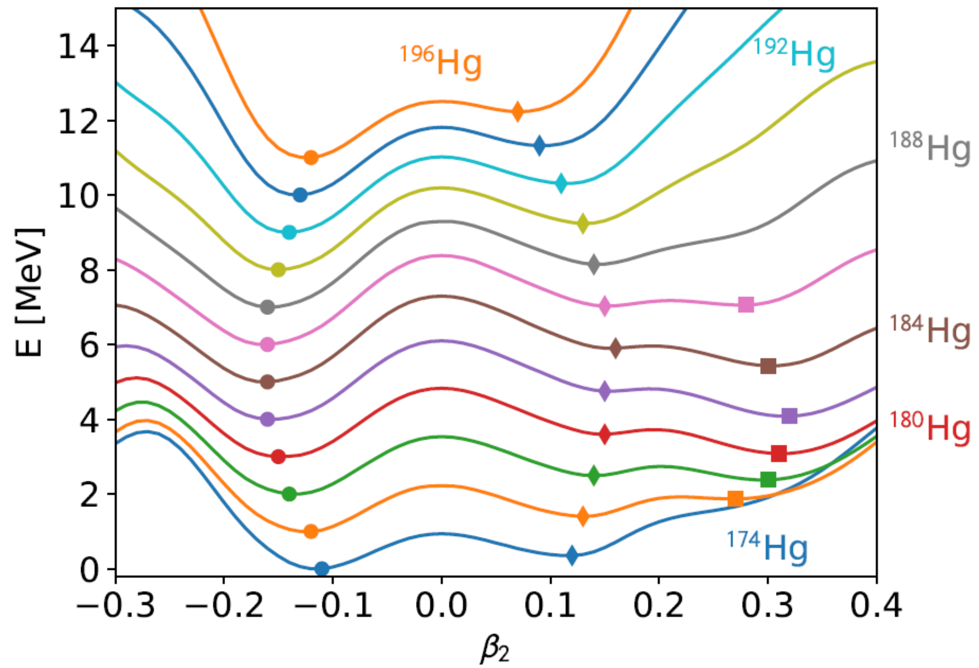


FIG. 11. Potential energy surfaces calculated using the UNEDF1$^{\mathrm{SO}}$ functional for even-mass mercury isotopes between $A = 174$ and A=196 as a function of the axial

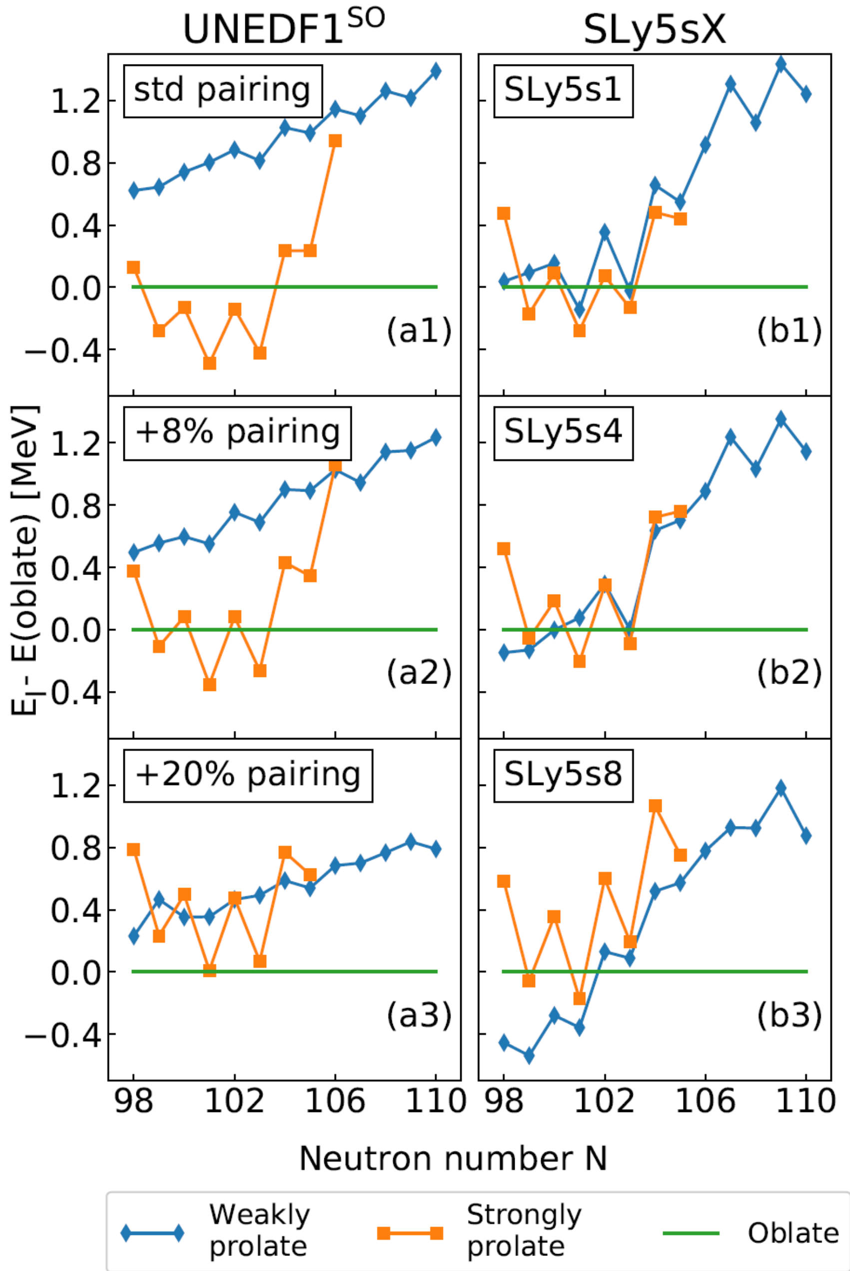


FIG. 12. Differences between energies of weakly and strongly prolate configurations and those corresponding to the oblate configurations, as calculated with UNEDF1$^{\mathrm{SO}}$ (left) and the SLy5sX parameterizations (right). For UNEDF1$^{\mathrm{SO}}$ calculations with standard pairing (top), pairing amplified by 8% (middle) and pairing amplified by 20% (bottom) are presented. For the SLy5sX family, results for SLy5s1 (top), SLy5s4 (middle) and SLy5s8 (bottom) are presented.

Some details of DFT calculations (changing pairing strenght or surface tension)

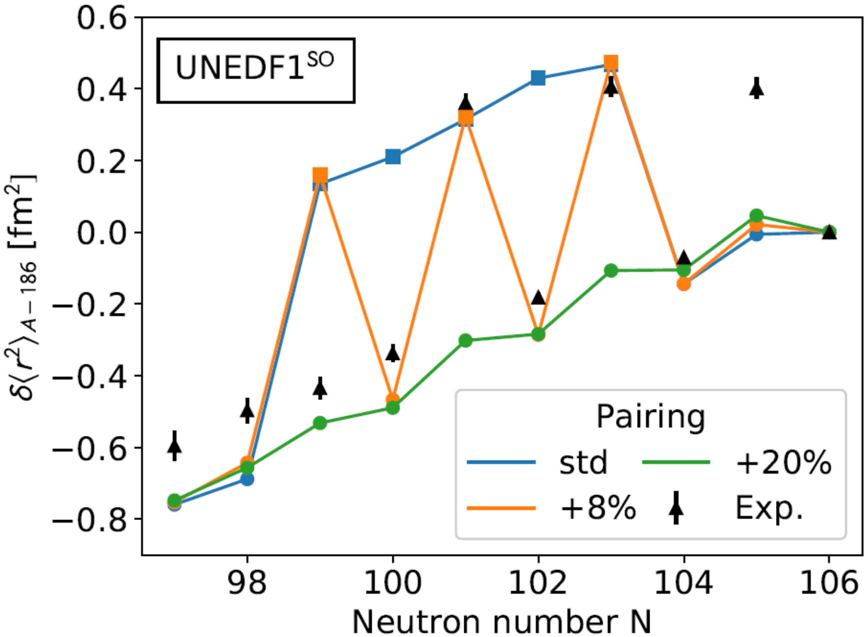


FIG. 13. Comparison of calculated isotopic shift using the UNEDF1^{SO} paramaterization for three different values of the pairing strength with experimental data, normalized to ^{186}Hg.

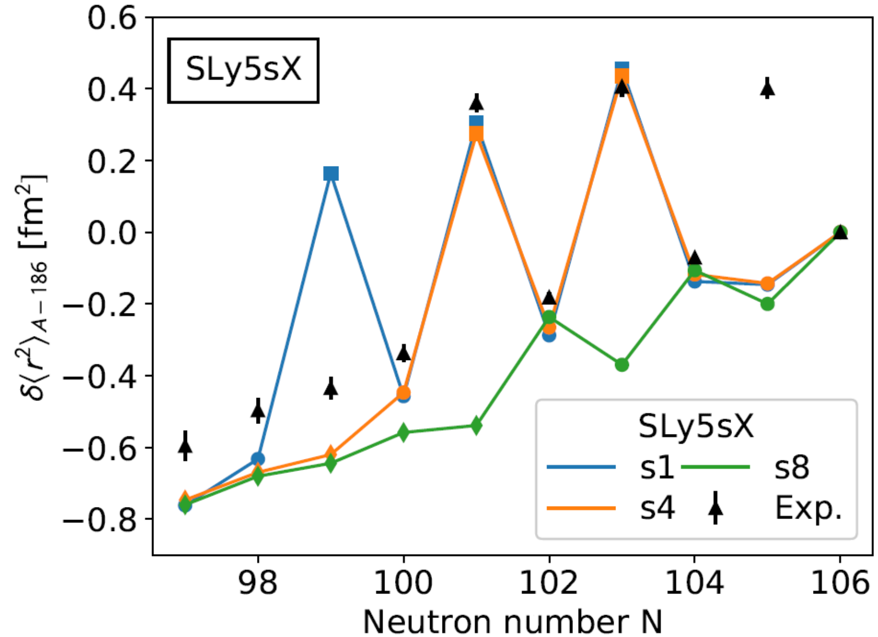


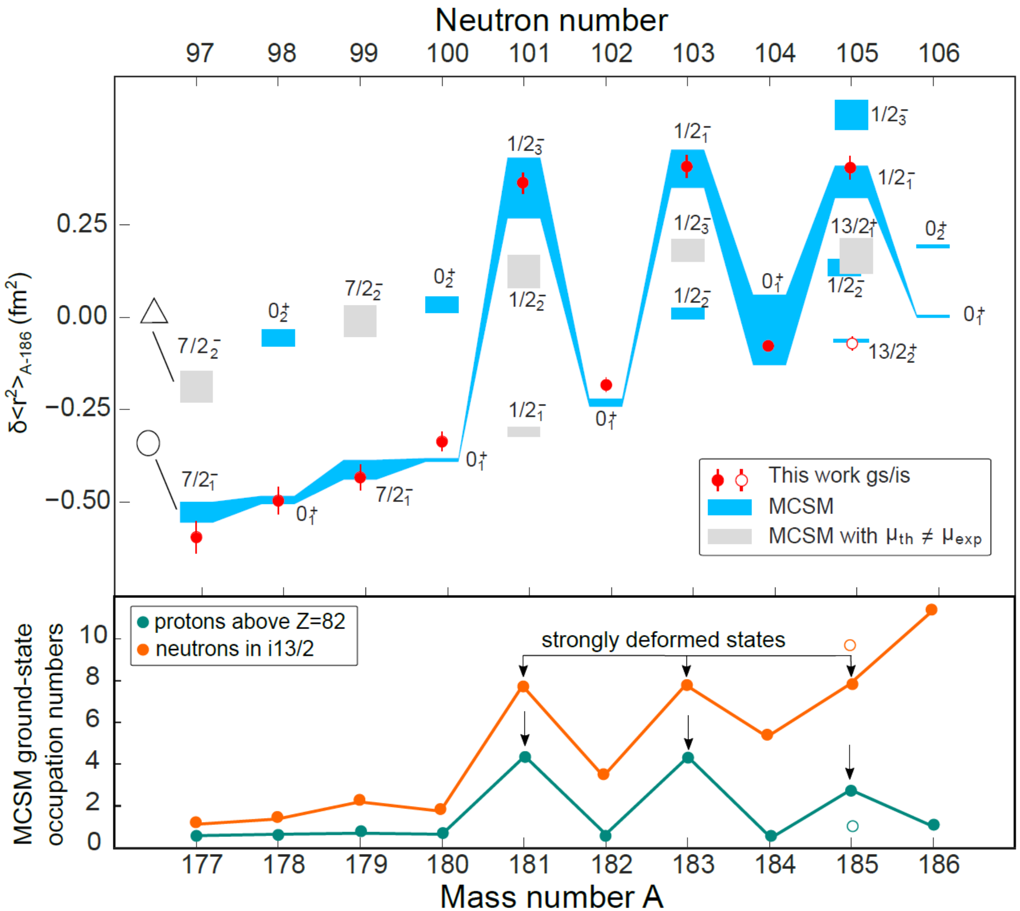
FIG. 14. Same as Fig. 13, but for the SLy5s1, SLy5s4 and SLy5s8 parameterizations.

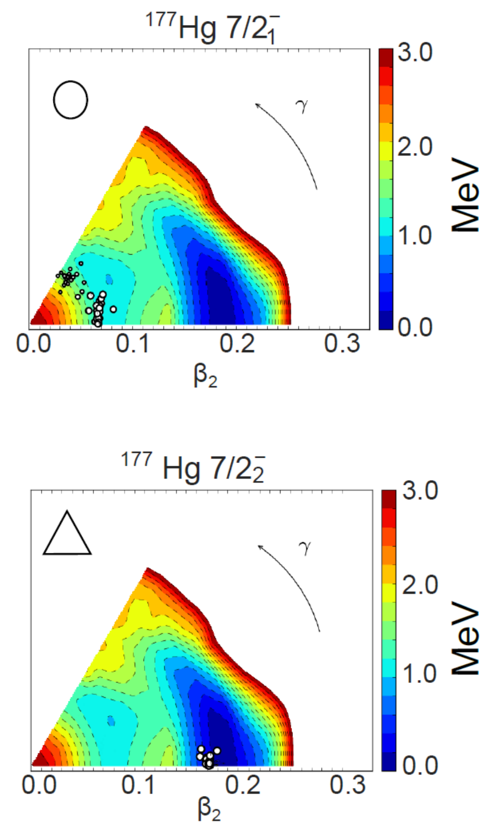
Mean-field theory summary:

- The gs radii staggering in Hg is a subtle effect of an interplay between closely-lying weakly oblate/prolate and strongly prolate shapes
- The effect is extremely sensitive to fine details of interactions, e.g. a slight change of pairing strength in UNEDF1^{SO} or change of surface tension in Sly5sX results in similar final pictures.
- This balance also depends on other properties of interactions, e.g. sp energies.
- Overall, no preference can be given between different approaches

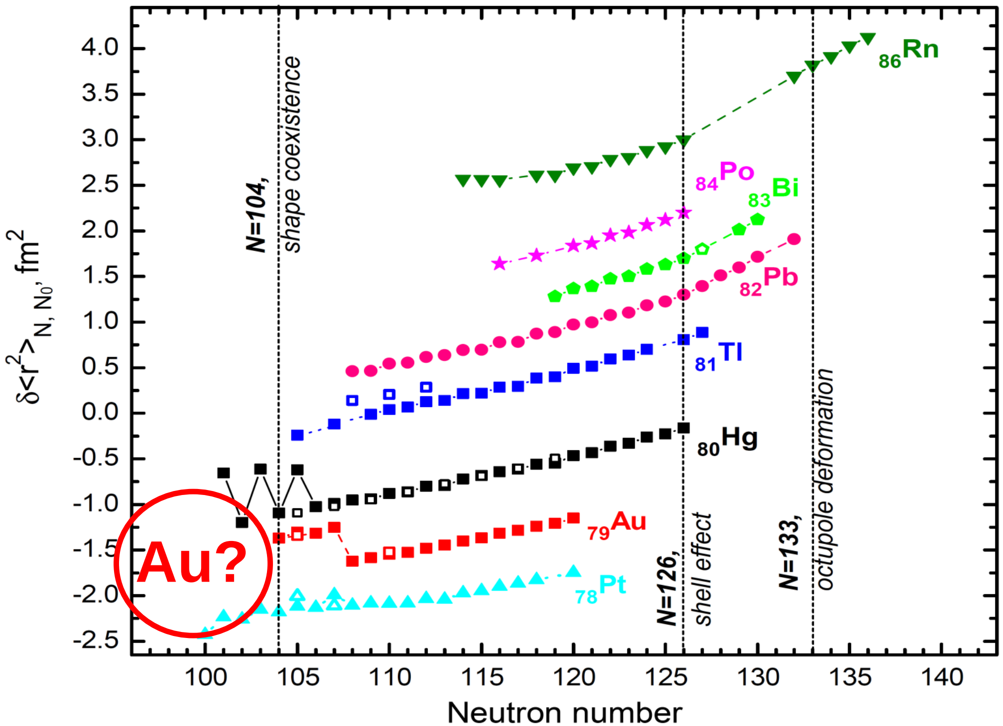
Monte-Carlo Shell Model (MCSM) Calculations for Hg isotopes (T.Otsuka et al)

- Largest calculation of its kind, avoids diagonalization of $>2\times10^{42}$-dimensional H matrix
- ^{132}Sn inert core, with up to 30 valence protons in $g_{7/2}$-$i_{13/2}$ and up to 24 valence neutrons in $h_{9/2}$-$j_{15/2}$
- Calculated magnetic (and quadrupole) moments
- Radii staggering due to increased proton occupancy of the $h_{9/2}$ intruder state coupled with larger neutron $i_{13/2}$ occupancy (driven by favourable monopole interaction between them)





IS534@ISOLDE: Charge radii of Au isotopes



- Are the light gold isotopes deformed, A(Au)<183?
- What are the spins of ground and isomeric states?

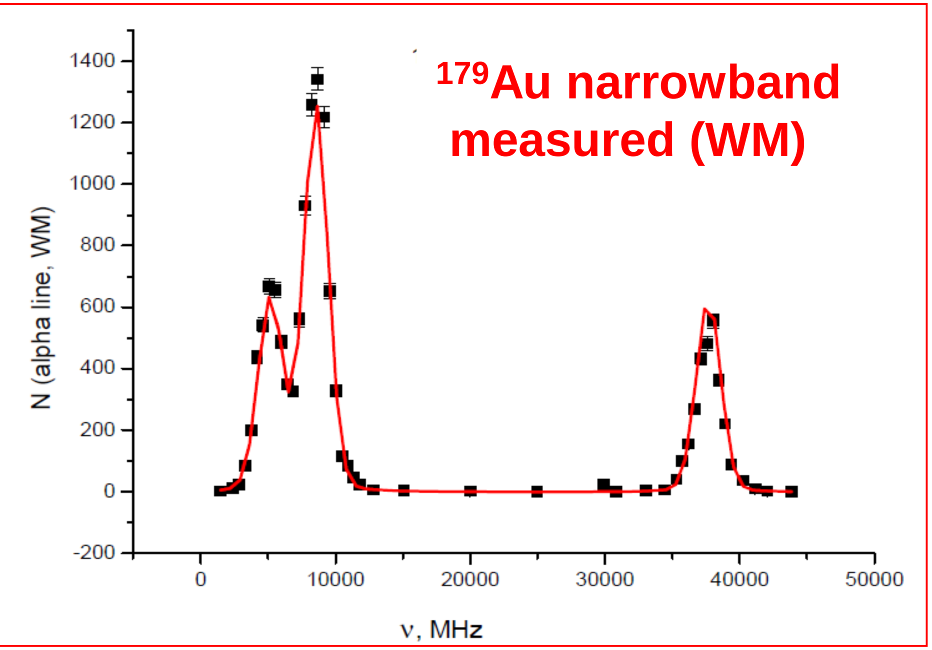
Previous radii data (ISOLDE)

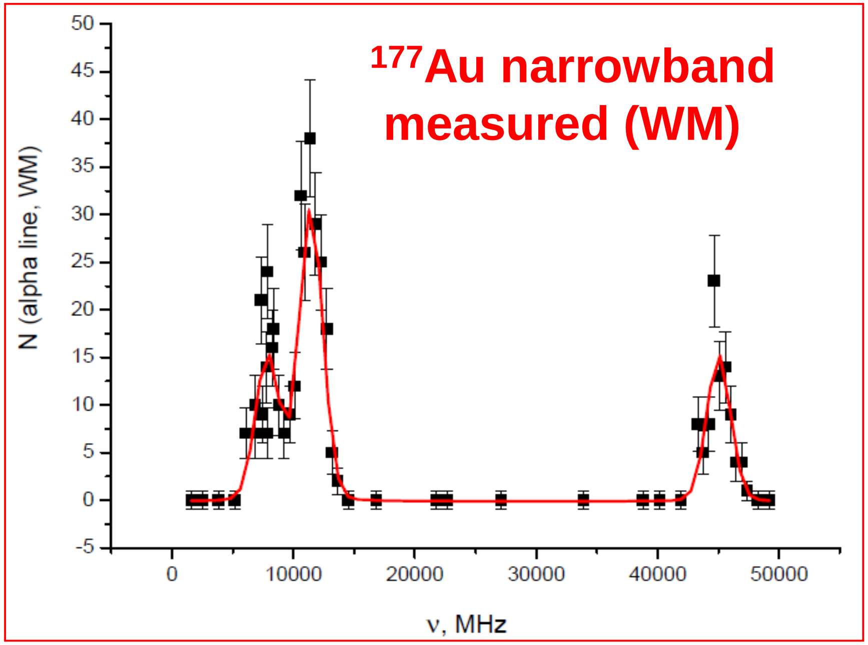
$^{185-190}$Au : K. Wallmeroth et al, NPA493,224 (1989)

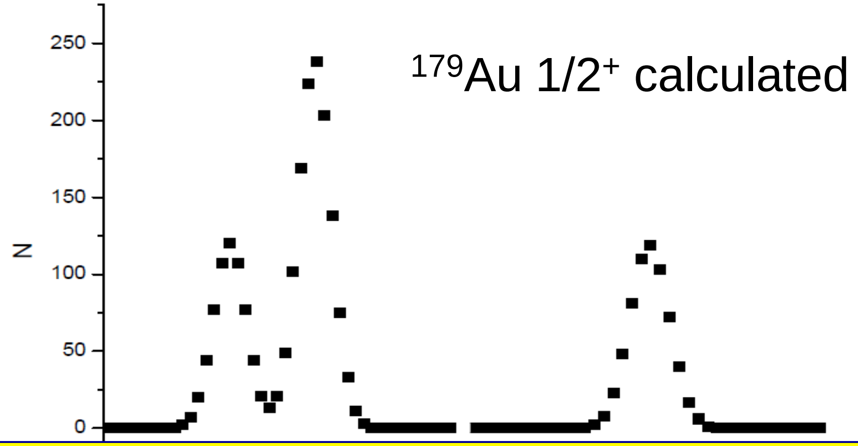
^{183,184}Au: U. Kronert et al, Z.Phys. A331, 521 (1988)

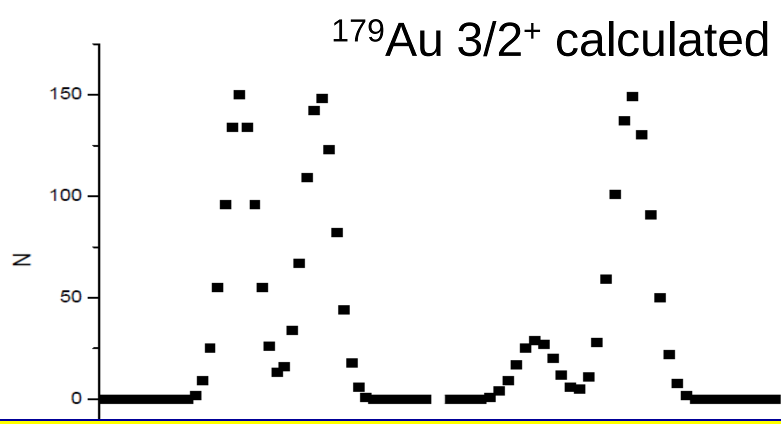
^{184mg}Au: F. Le Blanc et al. PRL79, 2213 (1997)

IS534: Nuclear spins for ^{177,179}Au extracted from HFS spectra









Based on the number of HFS components and their intensity ratio, the gs spins of ^{177,179}Au are experimentally determined as 1/2

(In)Famous Kink at N=126?

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Charge Radius Isotope Shift Across the $N = 126$ Shell Gap

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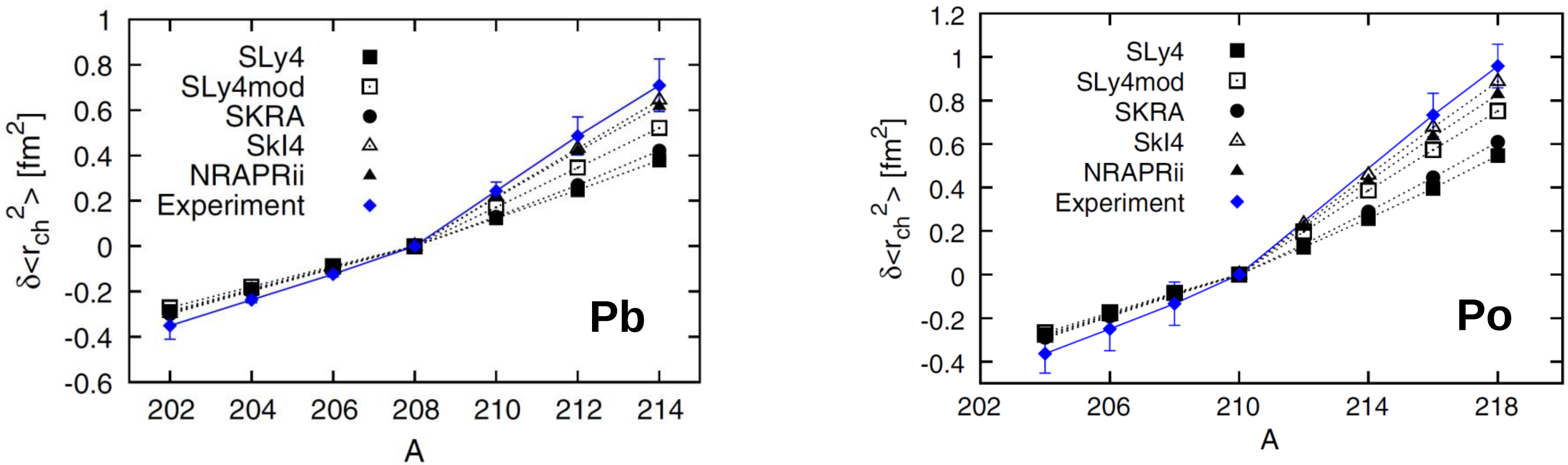

FIG. 1 (color online). Isotope shifts are given by the difference in the mean square charge radius between a series of even isotopes, denoted by their mass number A, and that of ^{208}Pb. Across the $N = 126$ shell closure, a strong increase in the slope of the experimental data (diamonds) is observed. Theoretical predictions, obtained with different Skyrme parametrizations, are also presented. Only a handful of Skyrme sets are able to reproduce the increase of slope above $N = 126$.

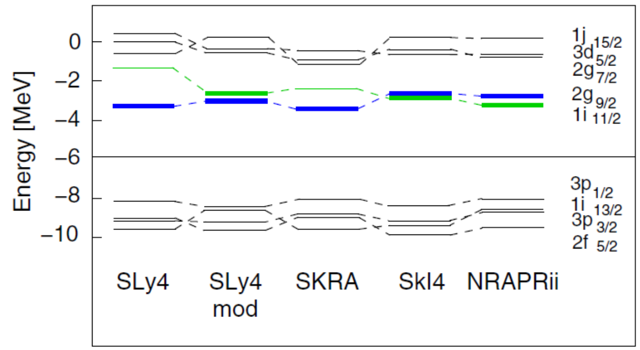

FIG. 3 (color online). Neutron single-particle energies around the Fermi surface in ^{210}Pb for five sets of Skyrme forces. States with a significant BCS occupation, $>3\%$, above $N = 126$ are emboldened. Whenever the $1i_{11/2}$ state is substantially populated, the kink in isotope shift can be reproduced.

Occupation of the neutron $1h_{11/2}$ orbital provides a better overlap with majority of n=1 proton orbitals (via symmetry energy), thus driving them to a larger radius?