In-source laser spectroscopy at ISOLDE – revealing peaks and plateaus in nuclear charge radii in the lead region

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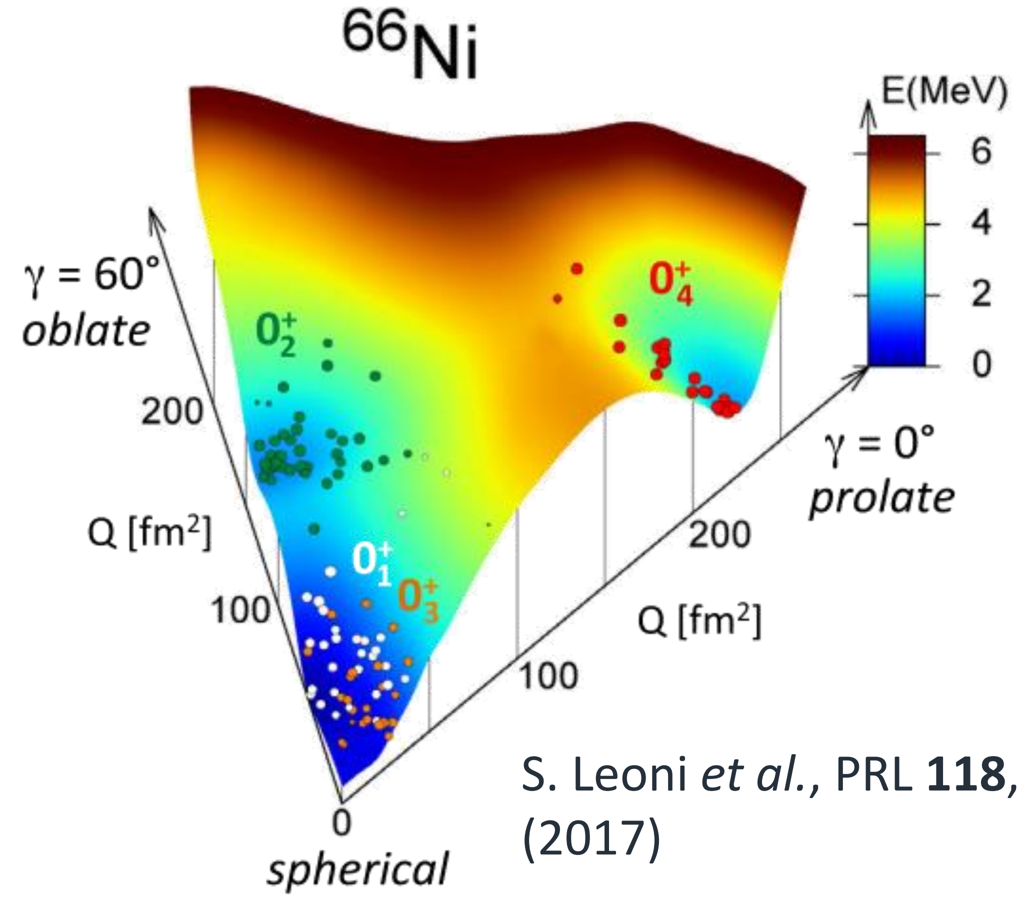
EURO-LABS
EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

Shape coexistence

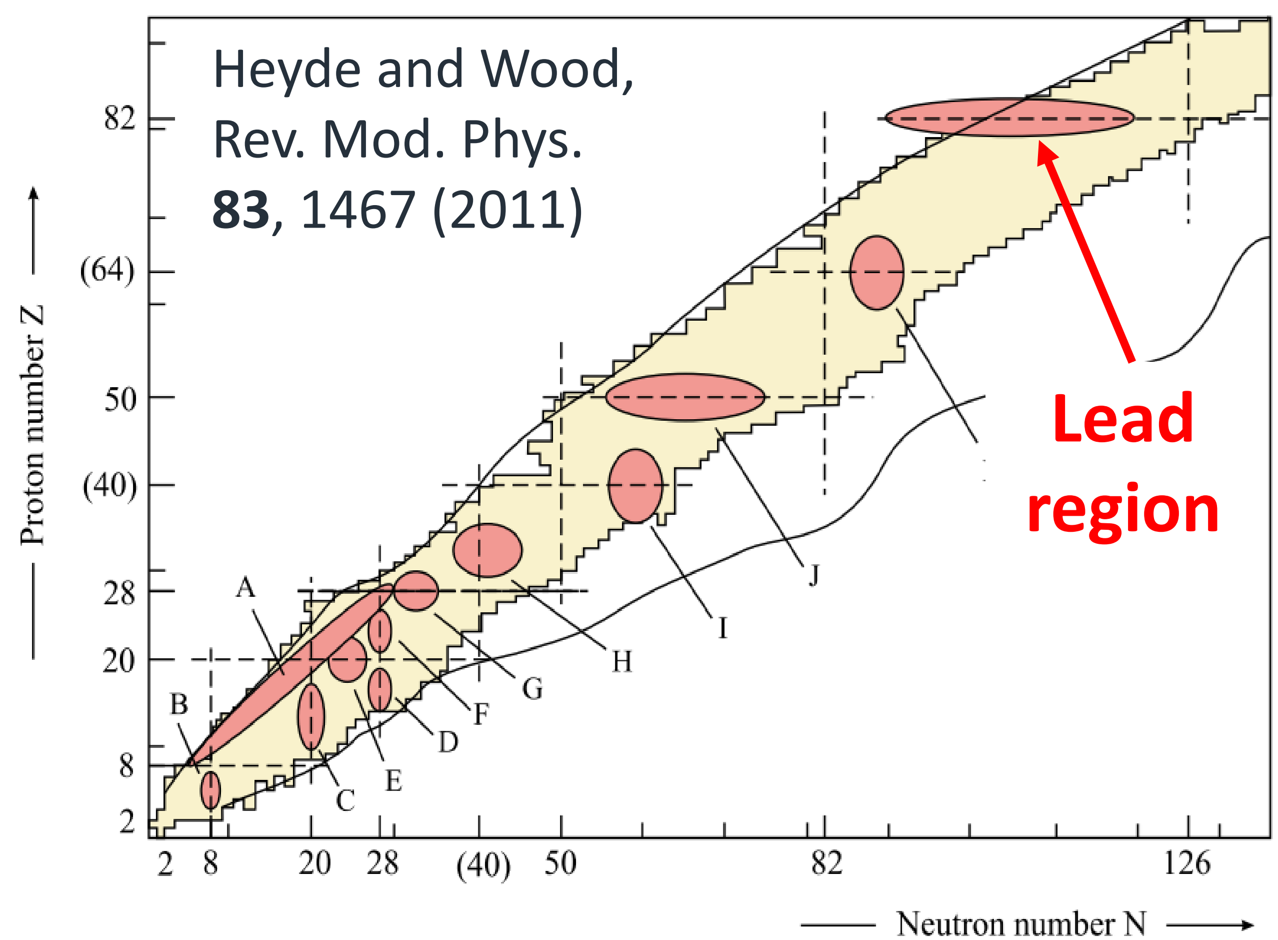
- Co-existing structures competing at low energies with distinctly different shapes
- Subtle interplay between stabilizing effects of closed shells and residual interactions between protons and neutrons
- Experimental data crucial for constraining models
- Appears all over the nuclear landscape

> The observation that a particular atomic nucleus (*N*, *Z* combination) can exhibit eigenstates with different shapes appears to be a unique type of behavior in finite many-body quantum systems.……………………………Understanding the occurrence of shape coexistence in atomic nuclei is arguably one of the greatest challenges faced by theories of nuclear structure.

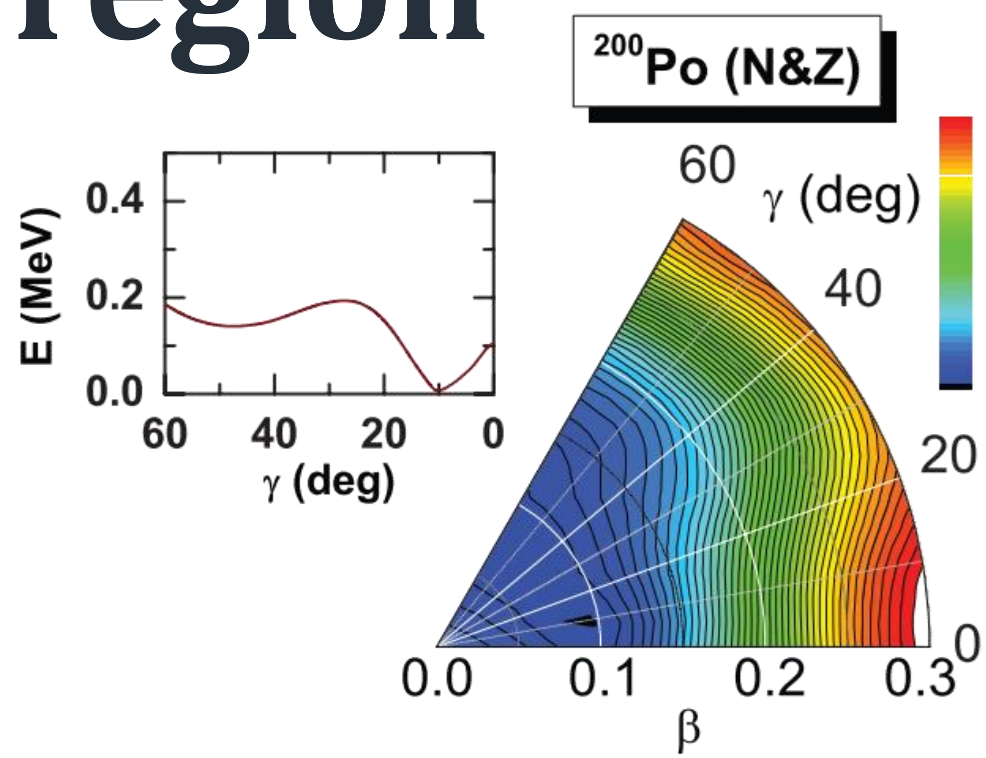
Heyde and Wood, *Rev. Mod. Phy.* **83**, 1467 (2011).

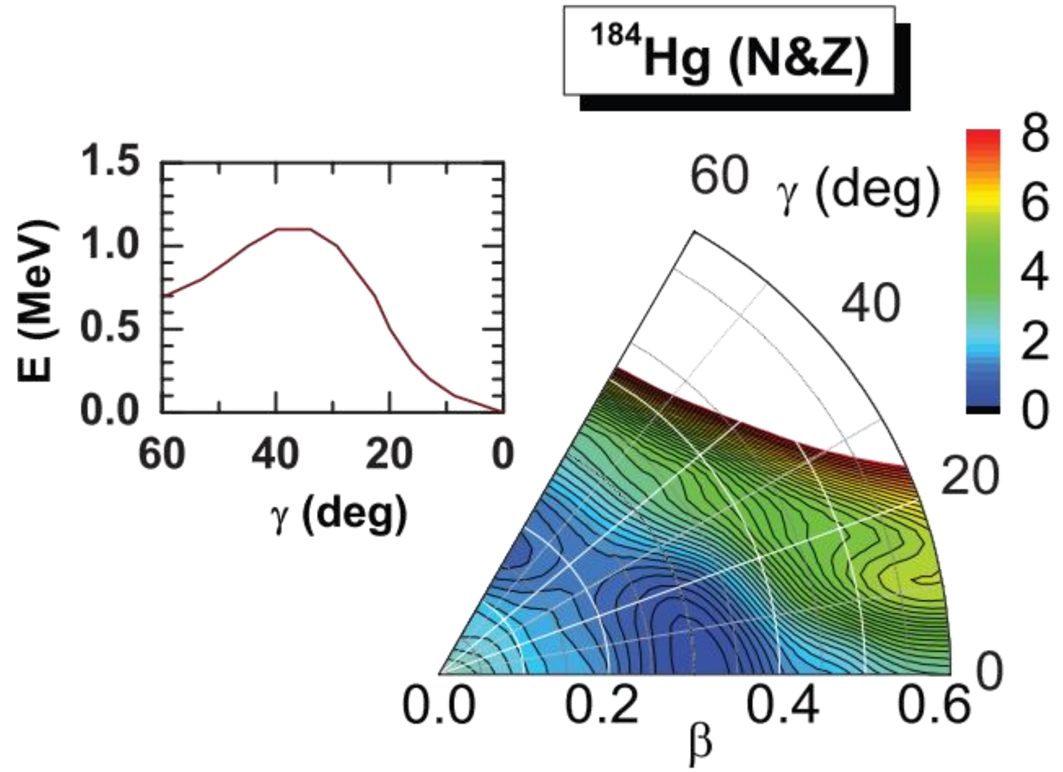


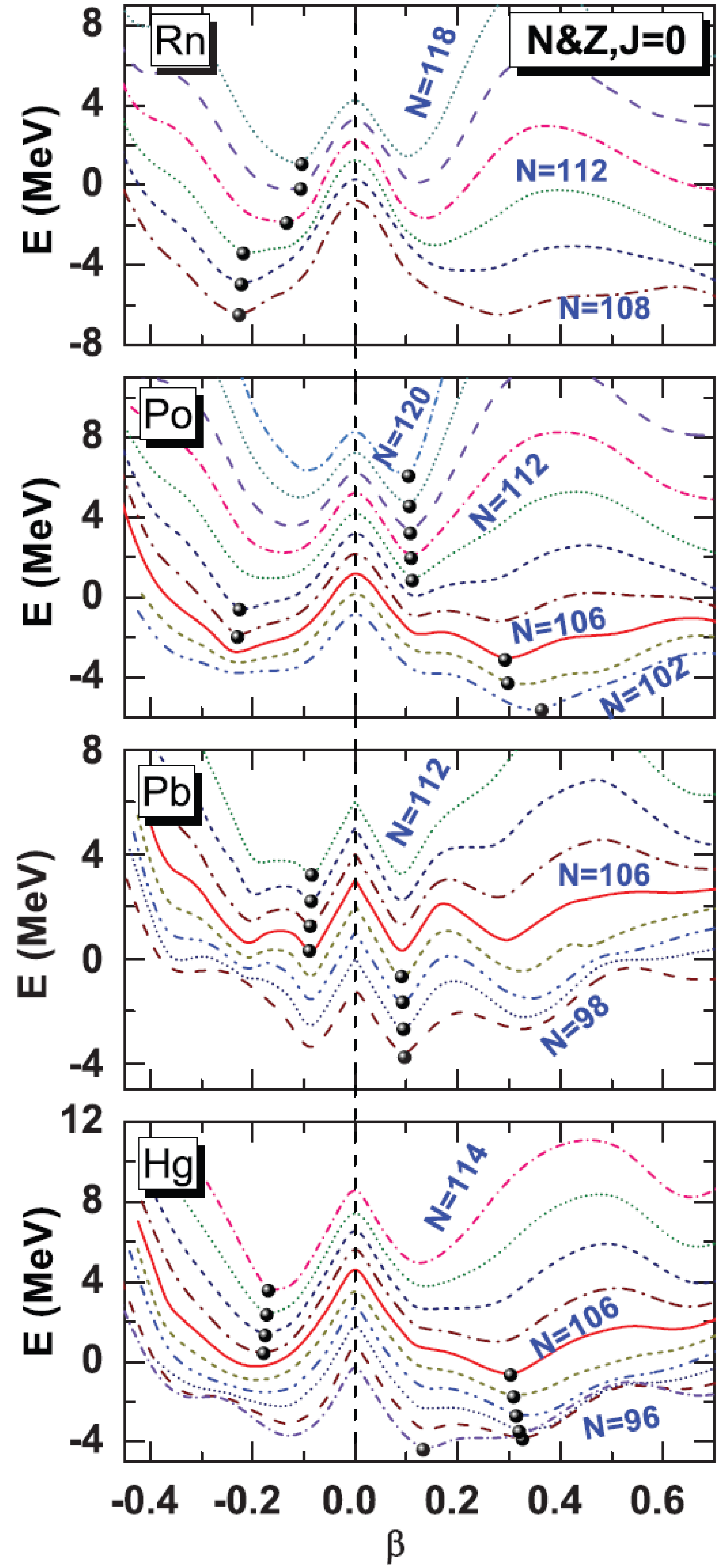
S. Leoni *et al.*, PRL **118**, 162502 (2017)



Shape coexistence in Pb region





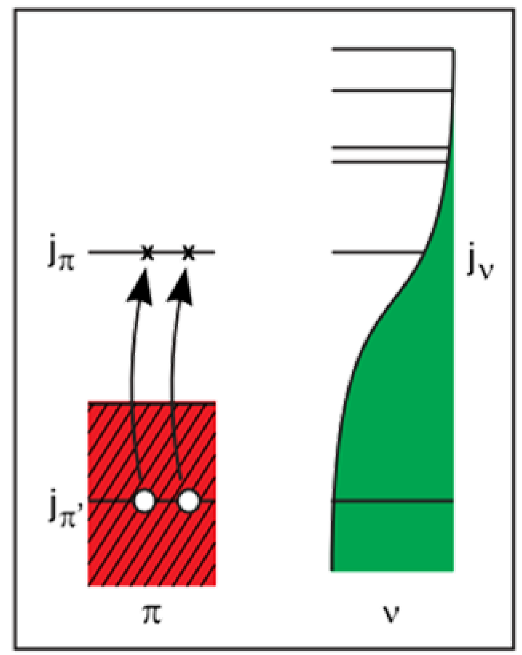


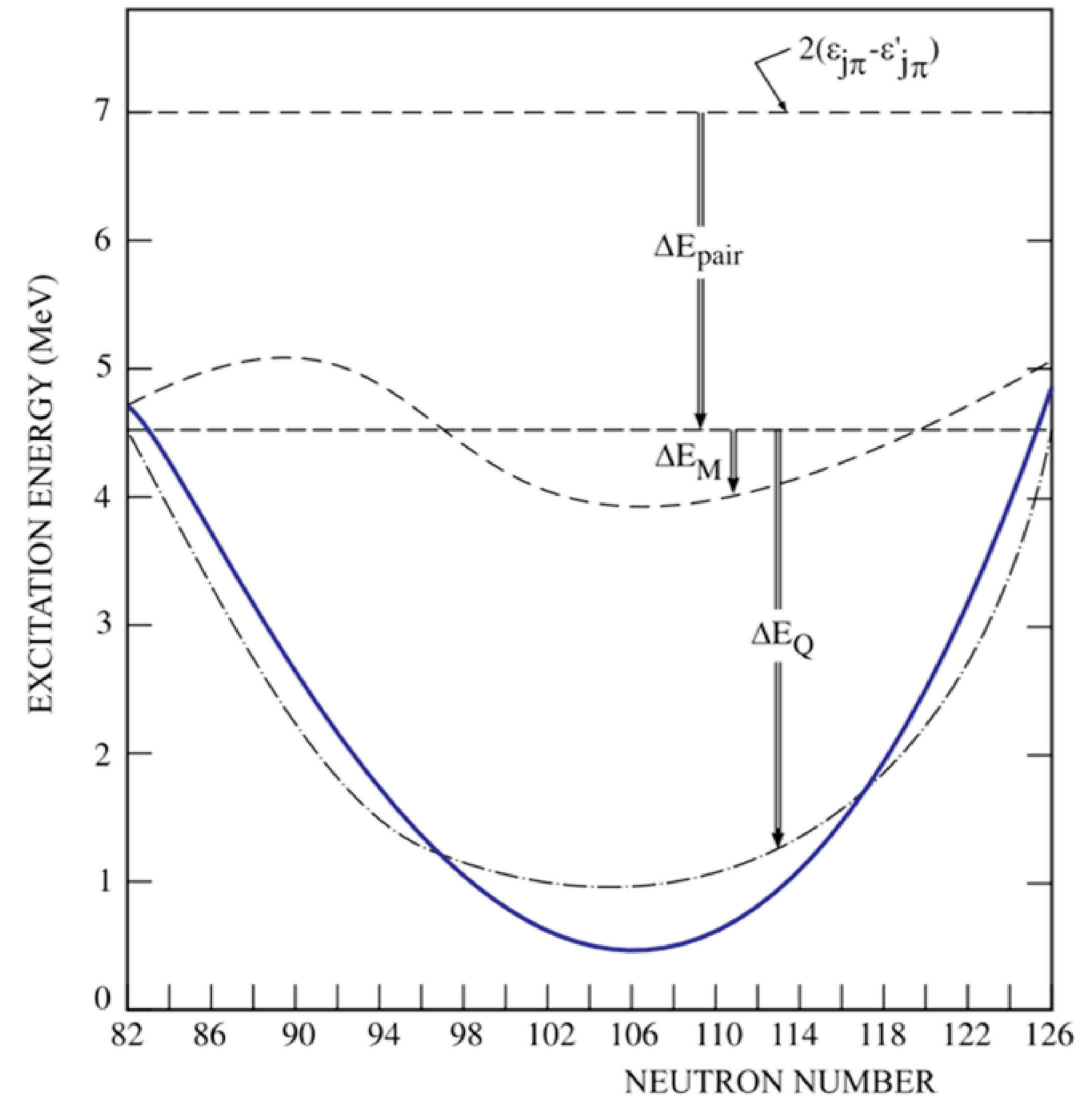
Yao, Bender & Heenen, PRC **87**, 034322 (2013)

Shape coexistence in Pb region

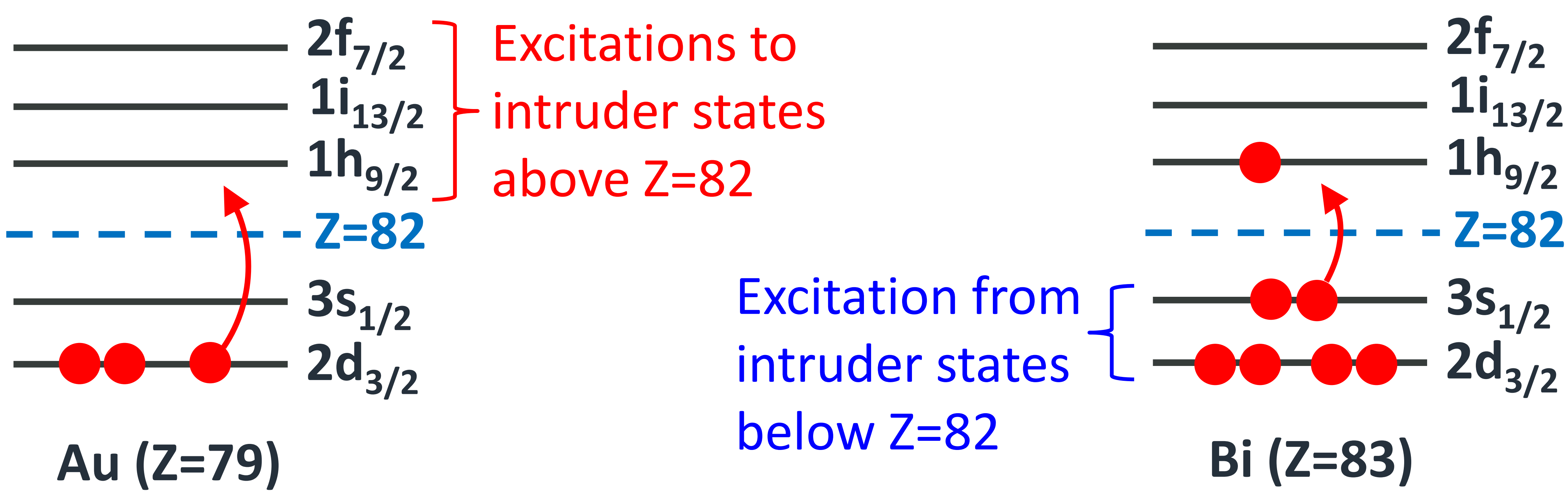
Heyde and Wood, Rev. Mod. Phys. **83**, 1467 (2011)

- “Classical” description is of particle-hole excitations across shell gaps, populating “intruder” states - energies of which reduced by residual interactions between nucleons

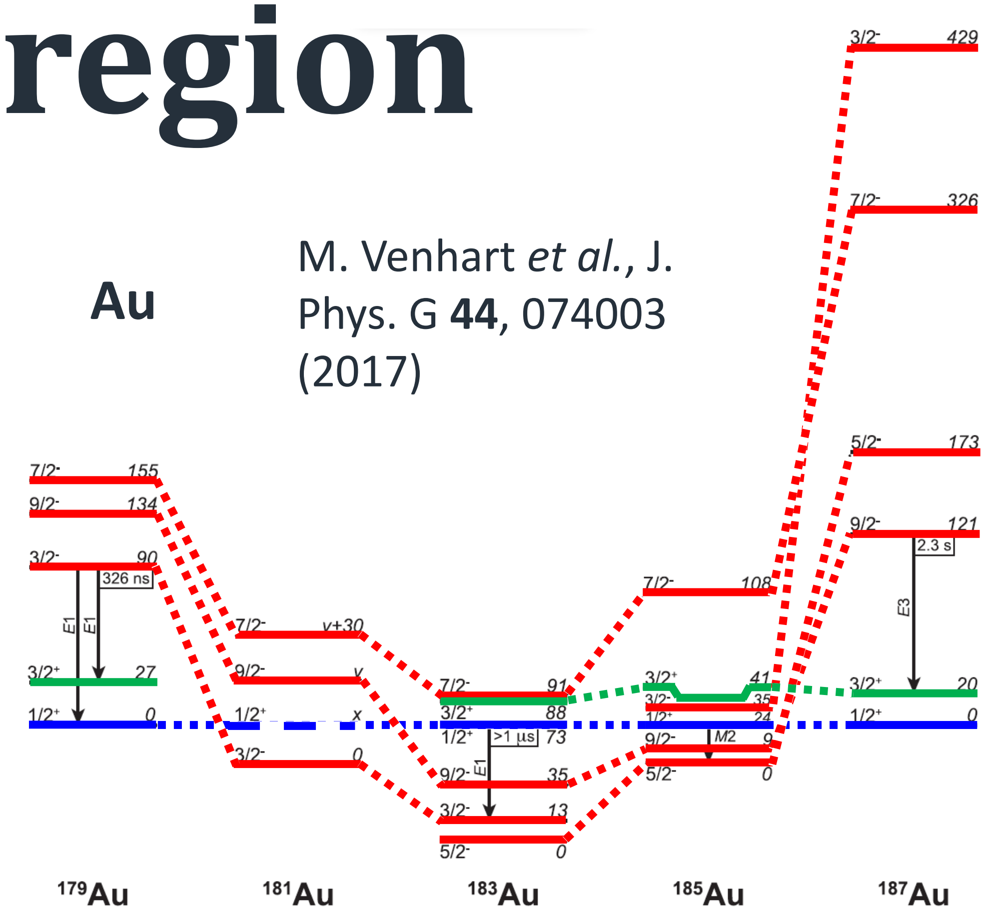




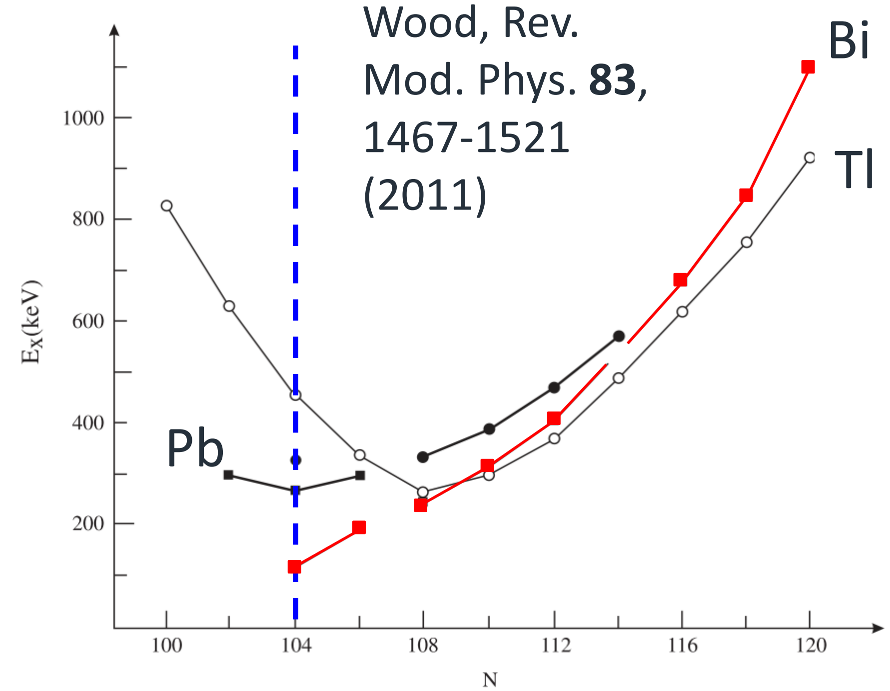
Culprits in the Pb region:



Shape coexistence in Pb region

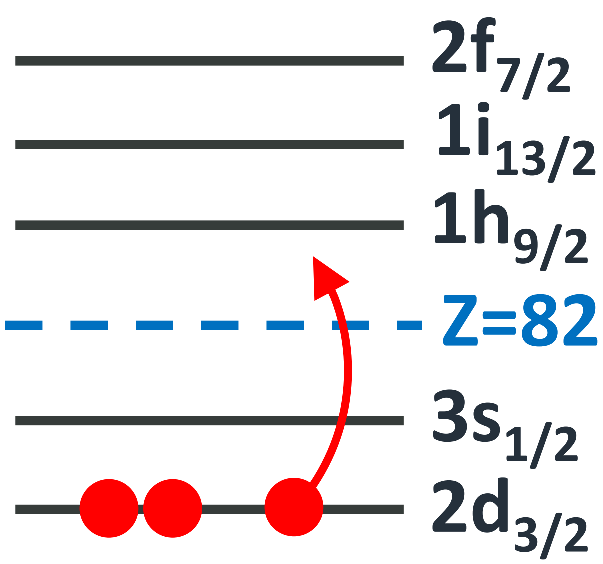


M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)



Heyde and Wood, Rev. Mod. Phys. **83**, 1467-1521 (2011)

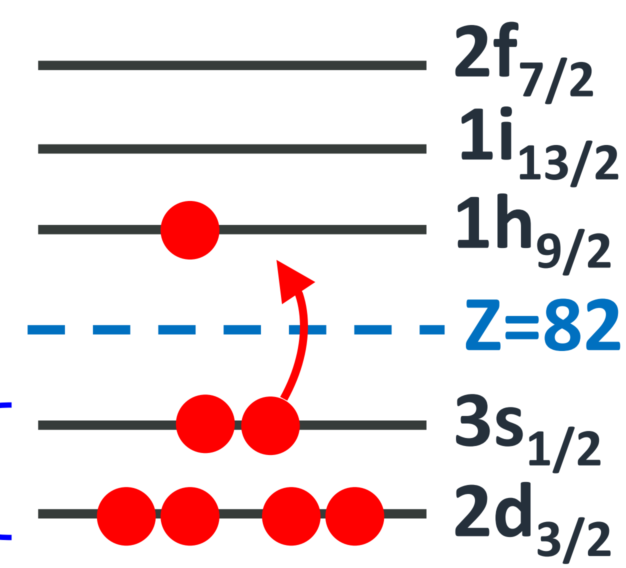
Culprits in the Pb region:



Excitations to intruder states above Z=82

Au (Z=79)

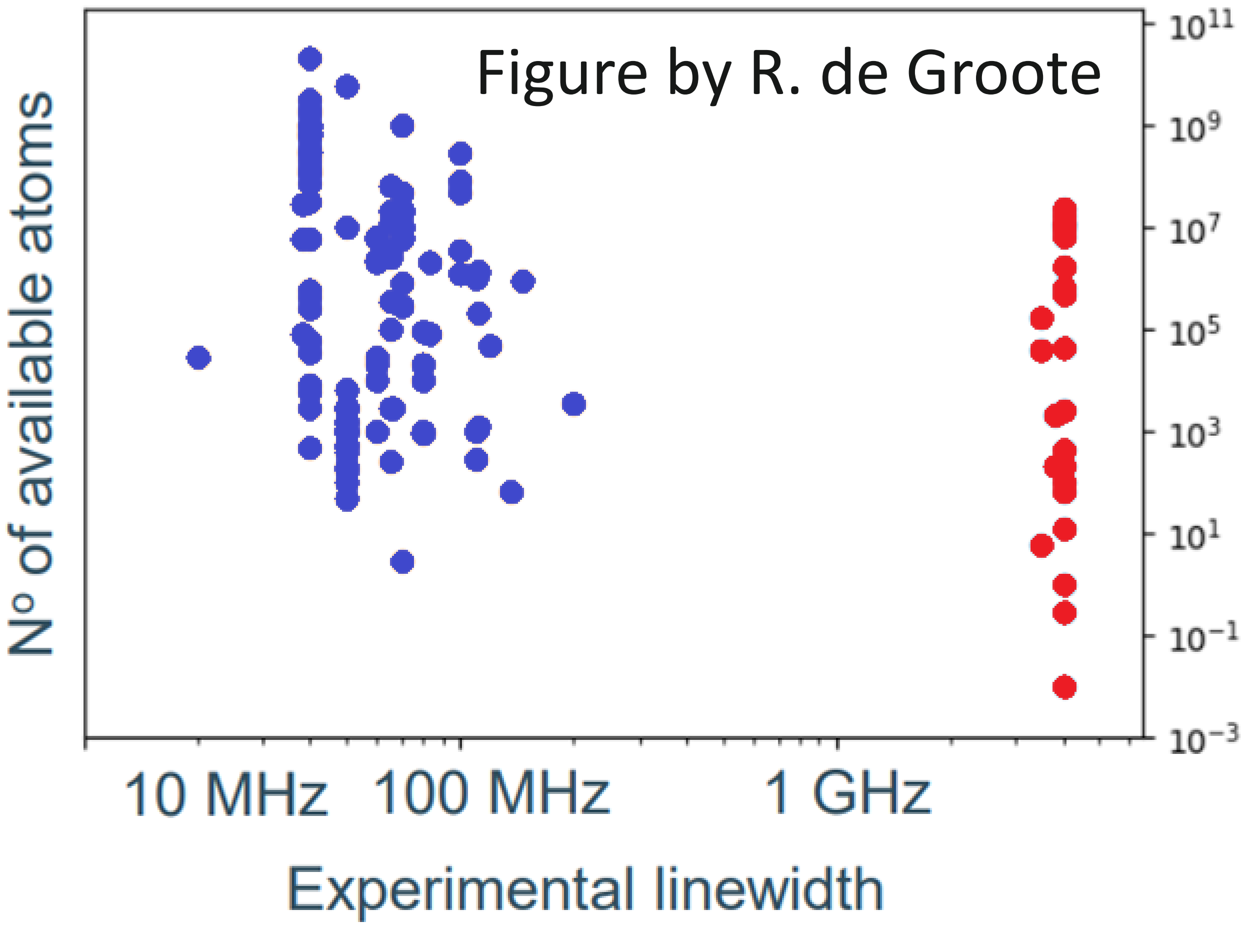
Excitation from intruder states below Z=82

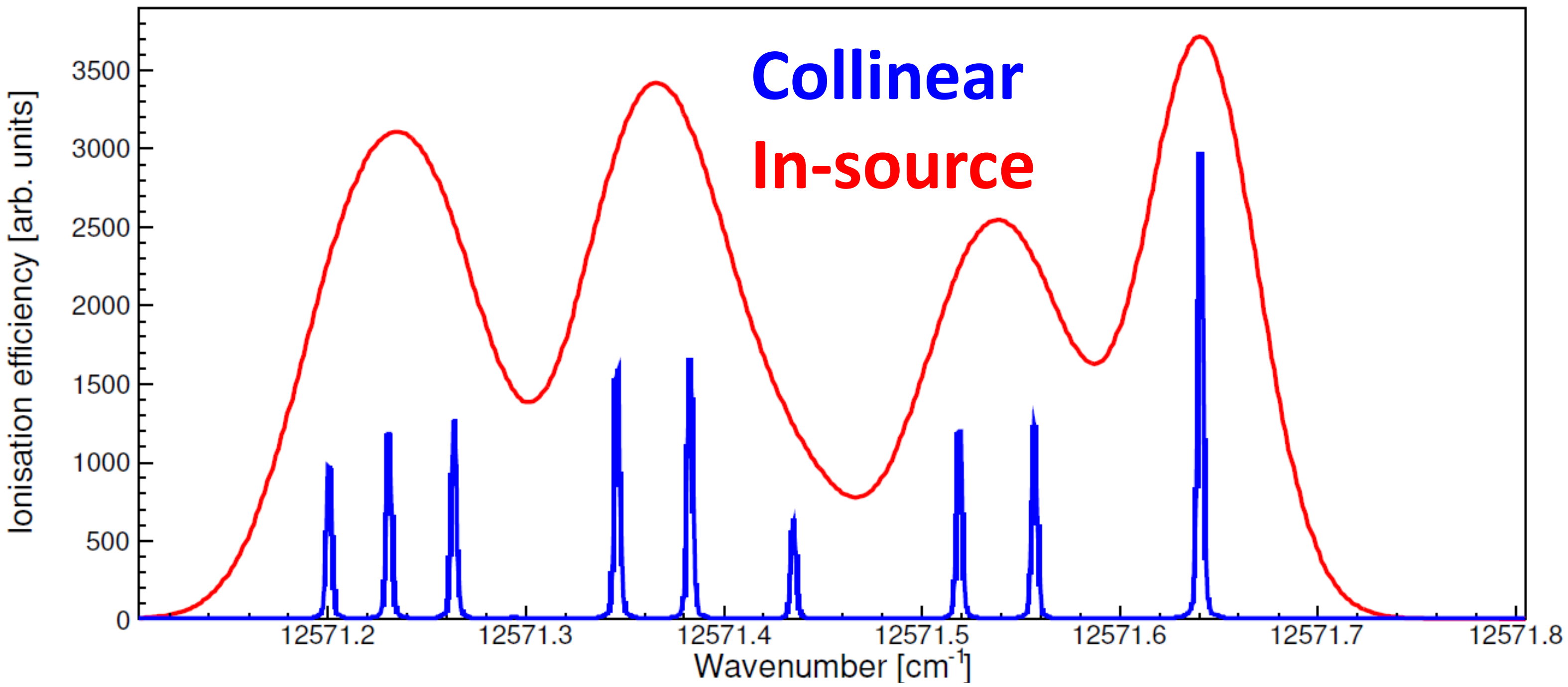


Bi (Z=83)

Laser spectroscopy @ ISOLDE

- Two groups representative of two methods:
  - **Collinear methods**
    - High resolution
    - Low efficiency
  - **In-source methods**
    - Low resolution
    - High efficiency

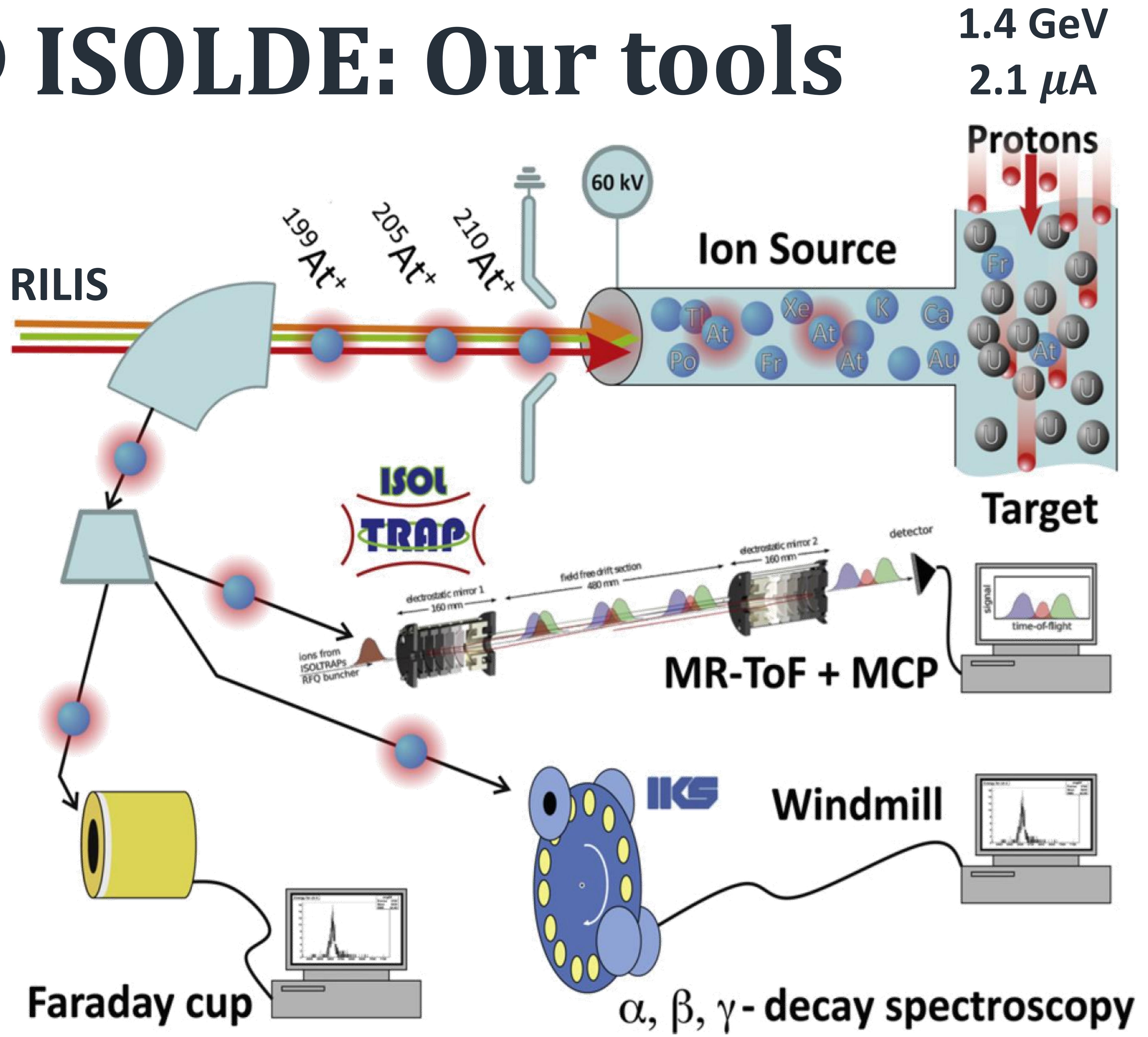




In source typically limited to radii and dipole moments, but can reach most exotic cases

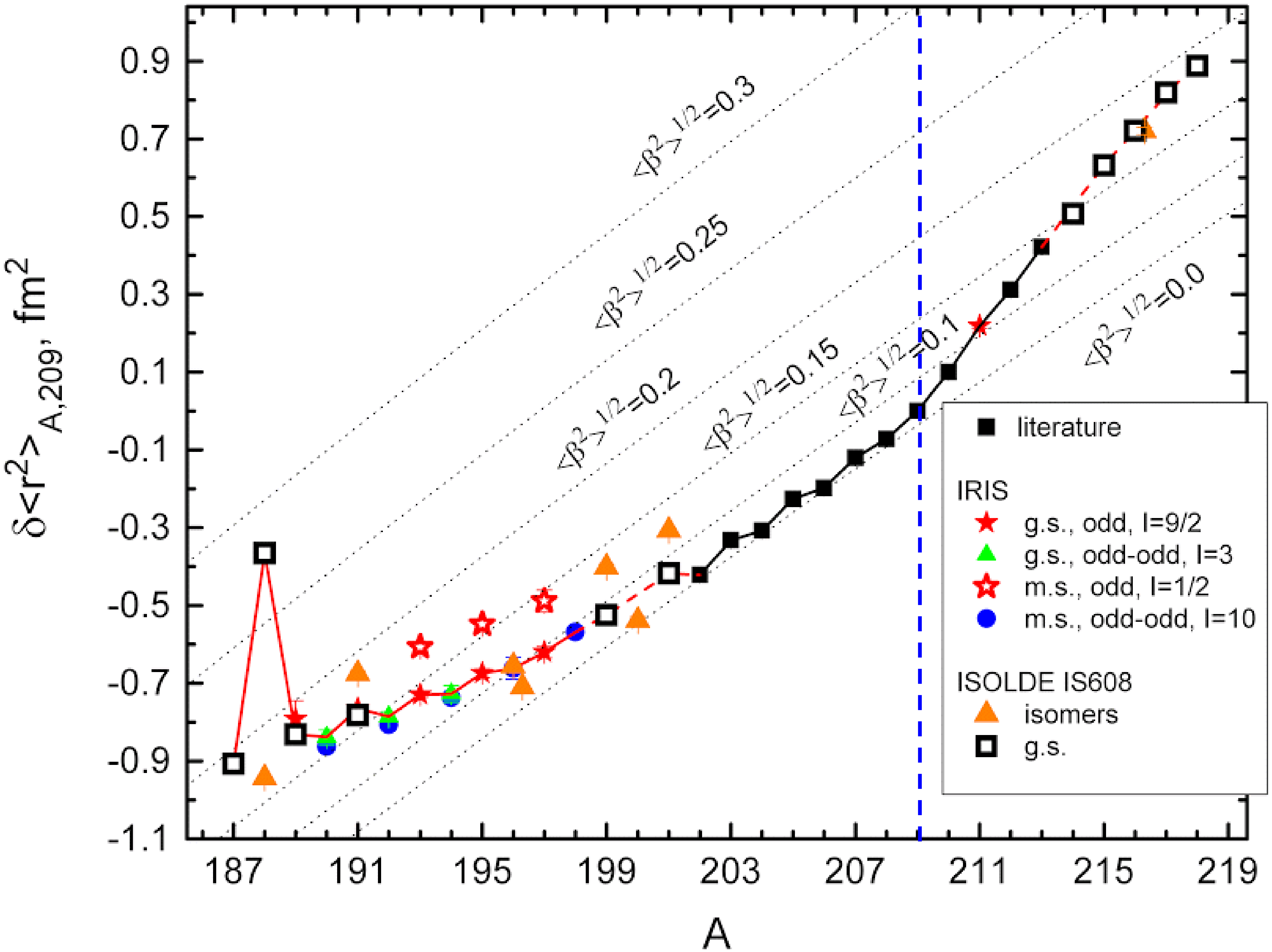
In-source @ ISOLDE: Our tools

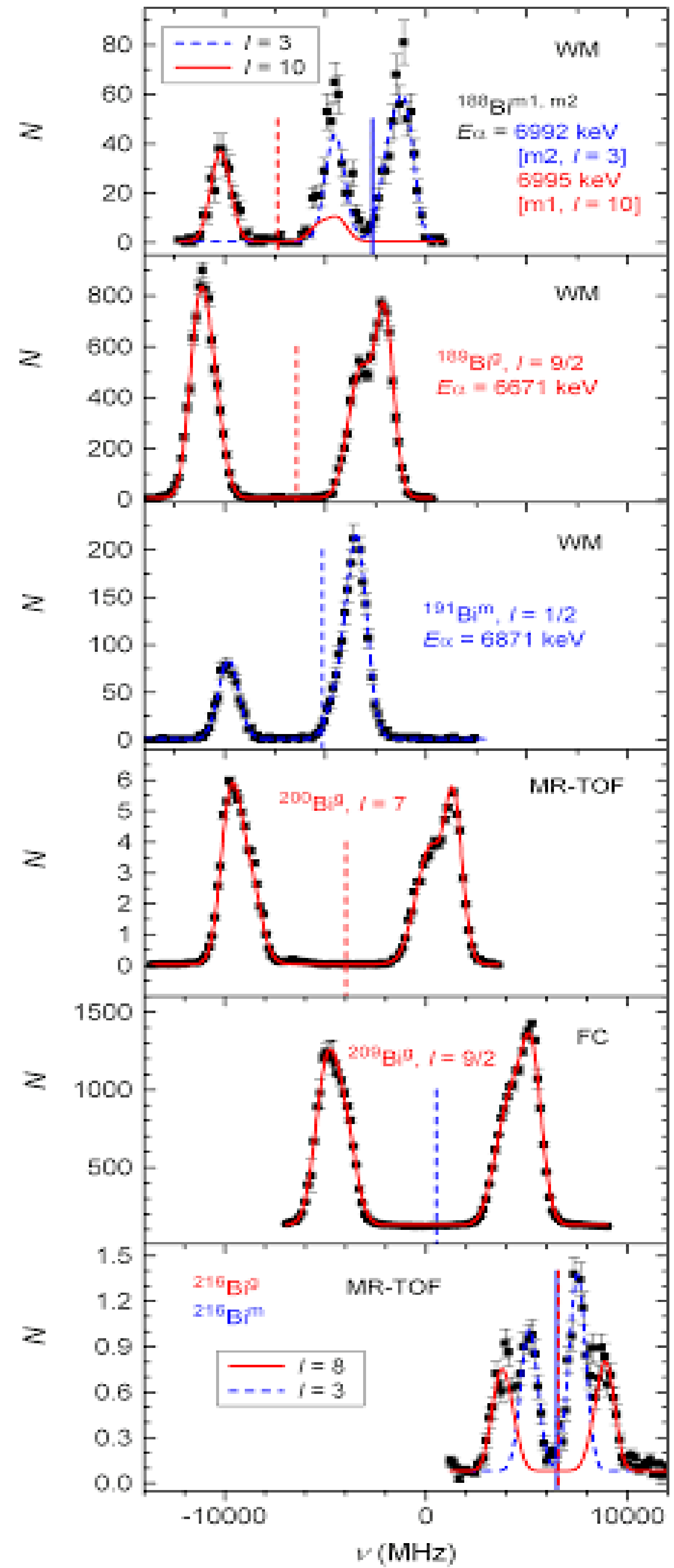
- Simple setups
- Quasi-background free
- **High sensitivity** and efficiency. Can deal with implantation rates down to ≈0.01 ions/sec.



Results from bismuth and gold campaigns

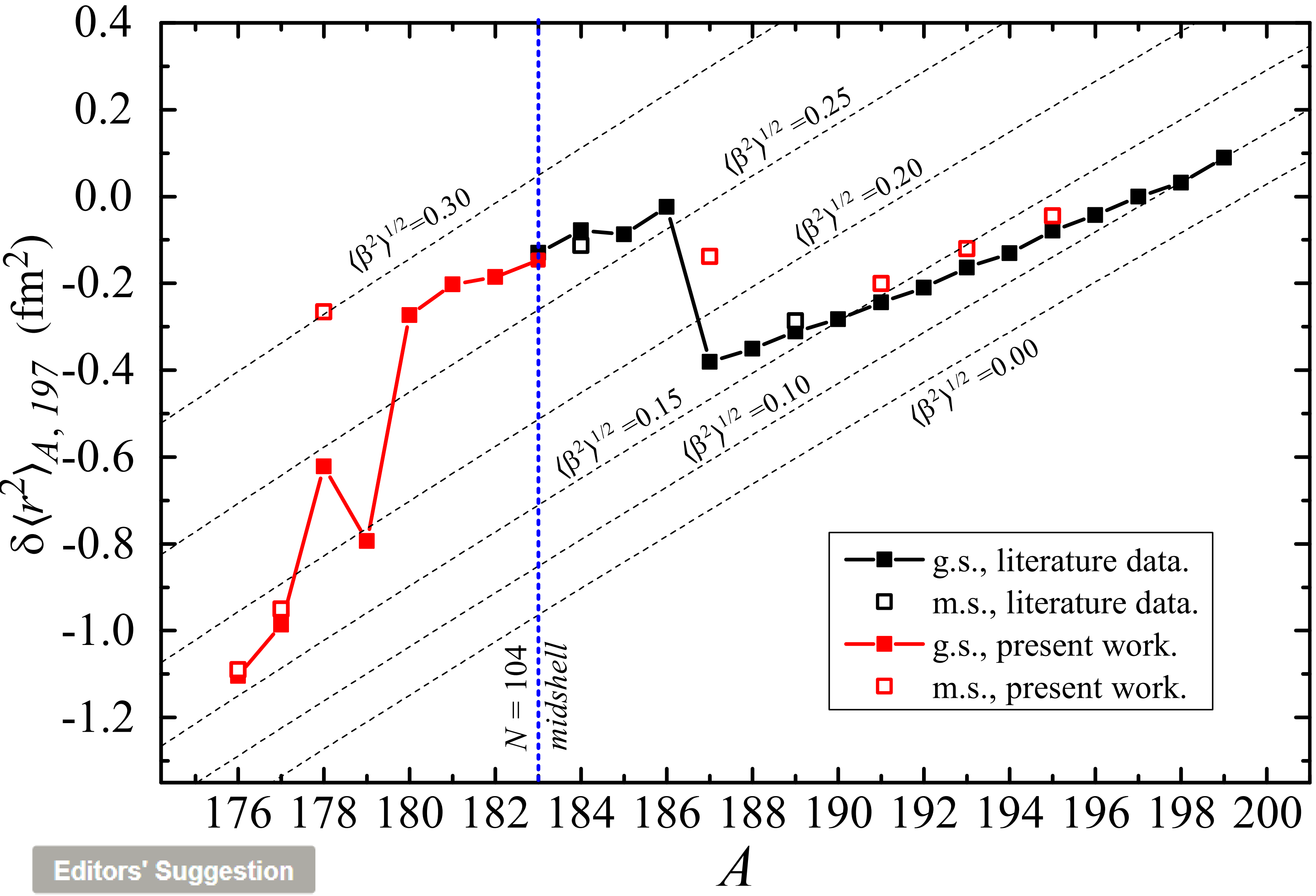
Bismuth radii (Z=83)

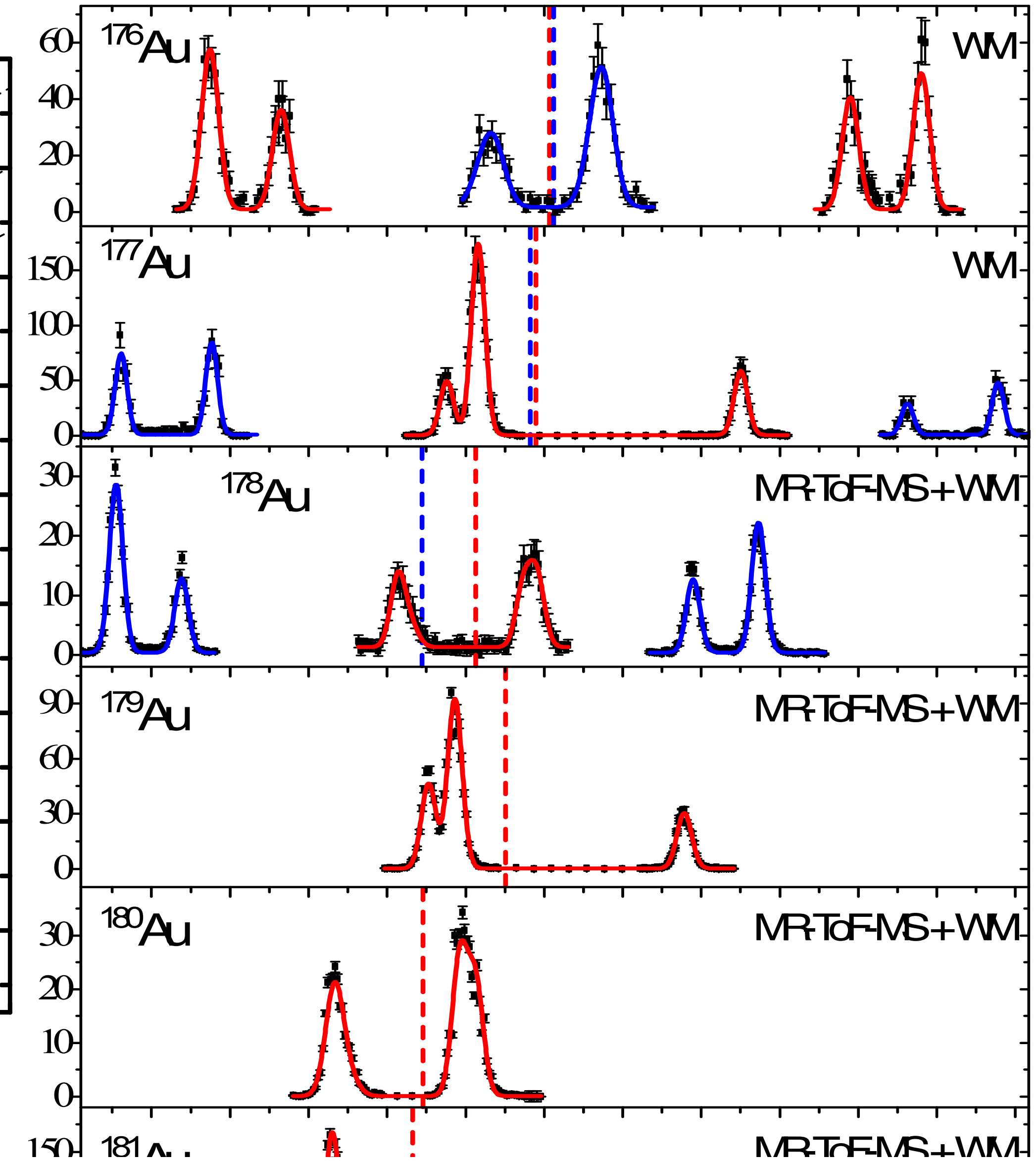




- **Results published: A.E. Barzakh *et al.*, PRL 127, 192501 (2021)**
- $^{189-209}$Bi – follow the spherical Pb trend
- Large isomer shifts in odd-A nuclei.
- N=126 “Kink” observed
- **^{188}Bi (N=105) – Large stagger!**

Gold radii (Z=79)



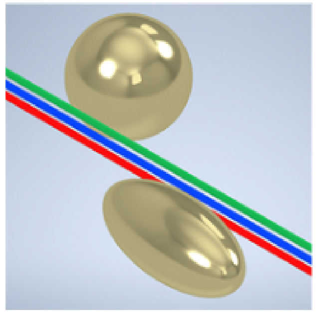


Editors' Suggestion

Deformation versus Sphericity in the Ground States of the Lightest Gold Isotopes

J. G. Cubiss *et al.*

Phys. Rev. Lett. **131**, 202501 (2023) – Published 14 November 2023



Charge radii of neutron-deficient gold isotopes measured with resonance-ionization laser spectroscopy display a unique pattern that has not been observed elsewhere in the nuclear chart.

Show Abstract +

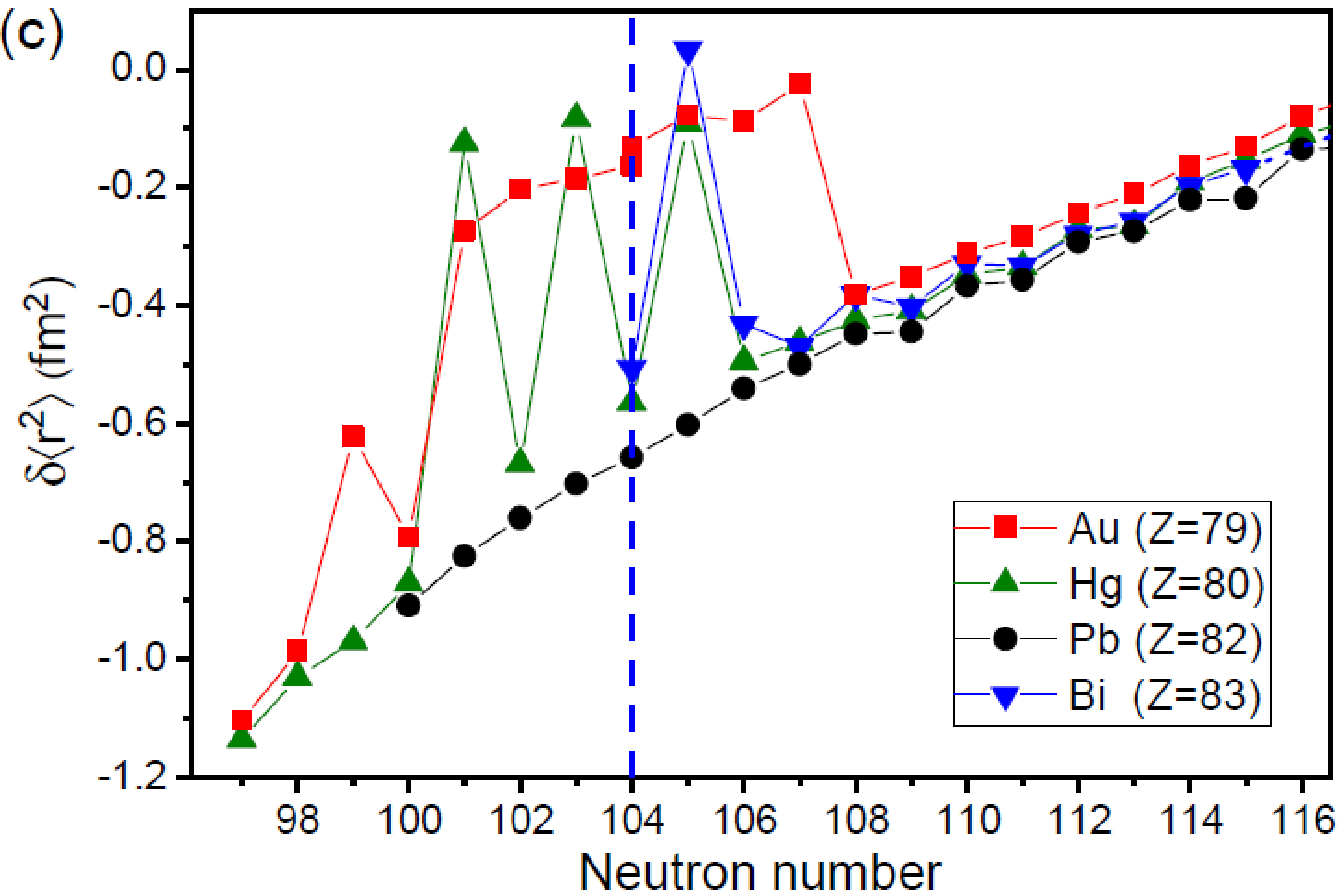
News › News › Topic: Physics

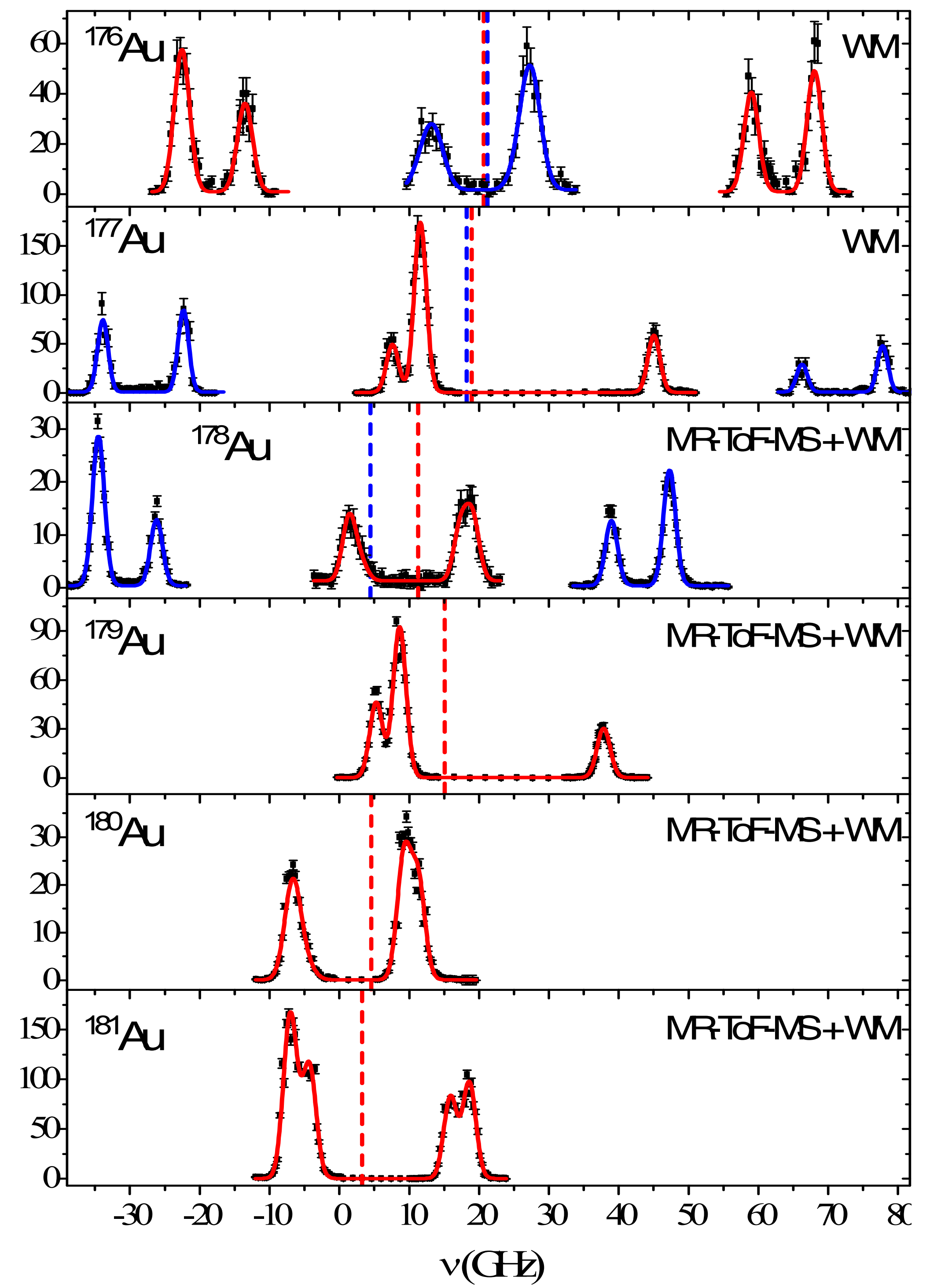
ISOLDE sees shape shifting in gold nuclei

The finding comes a little more than 50 years after the phenomenon was first discovered at the facility in mercury nuclei

15 NOVEMBER, 2023

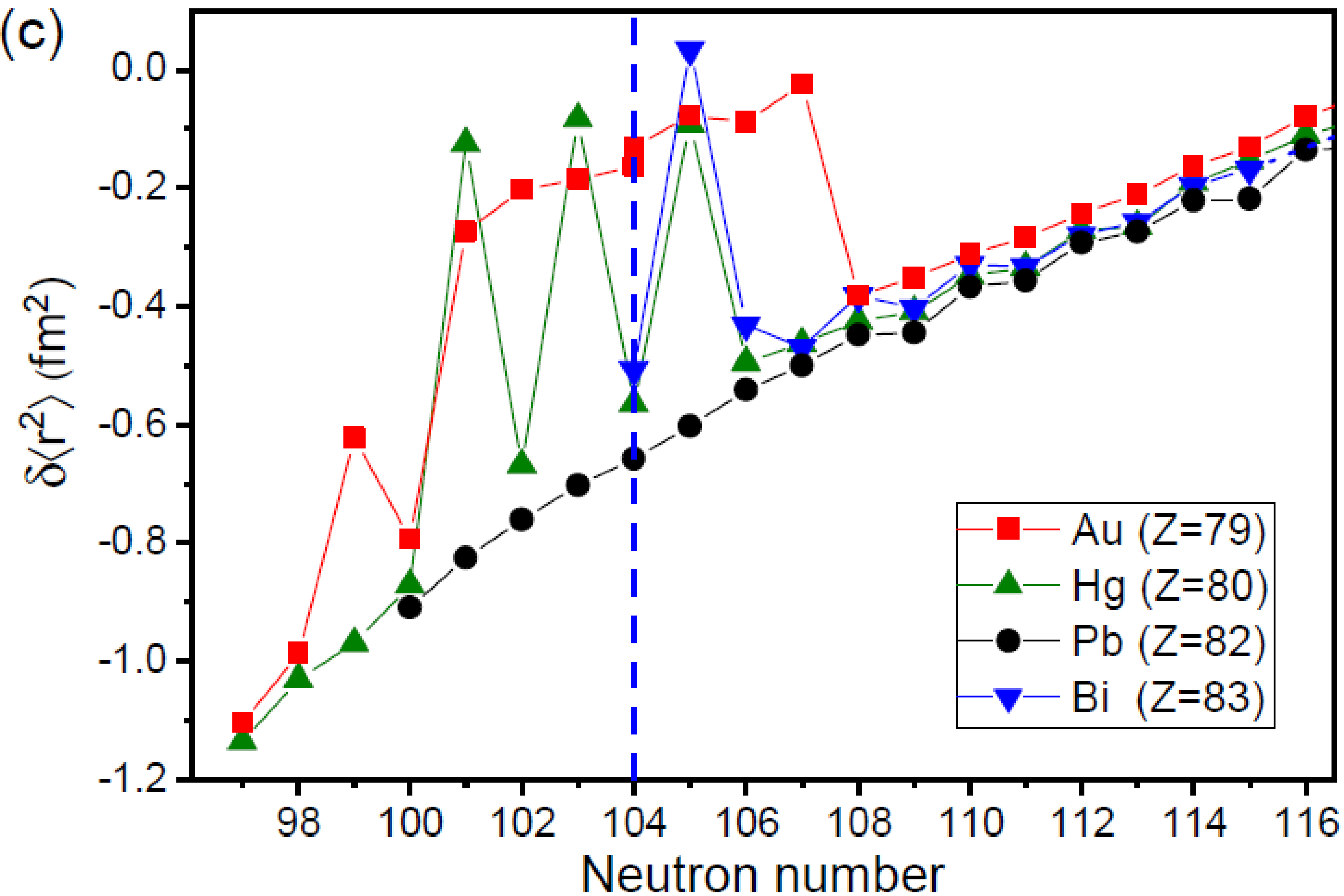
Gold radii (Z=79)

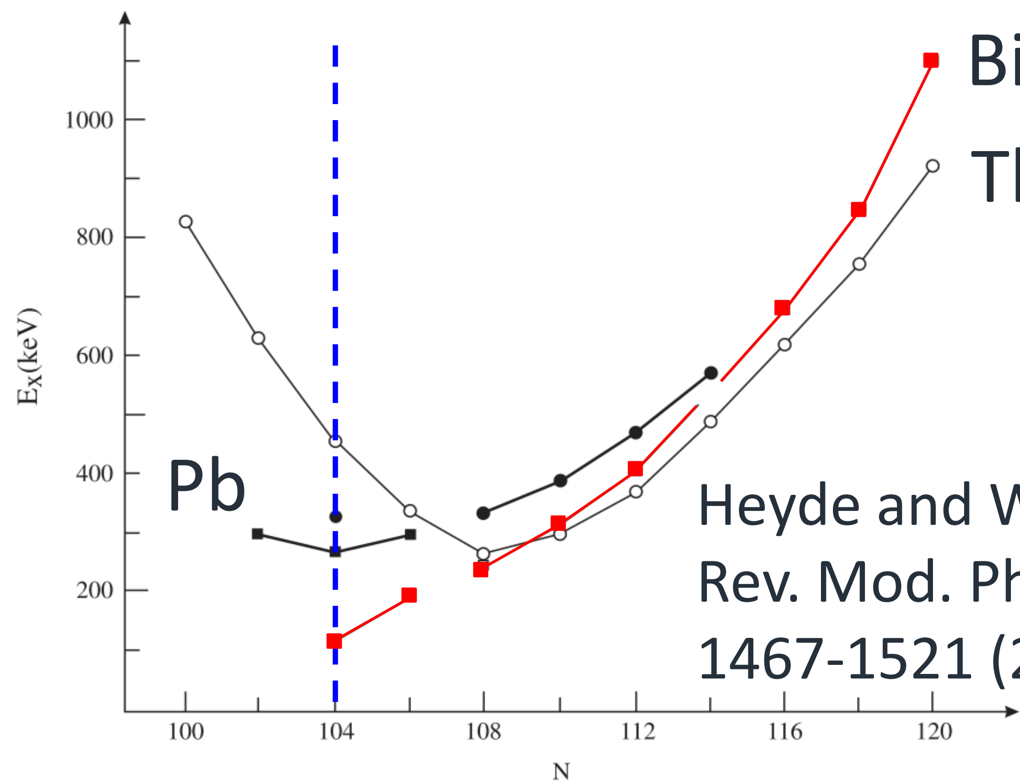




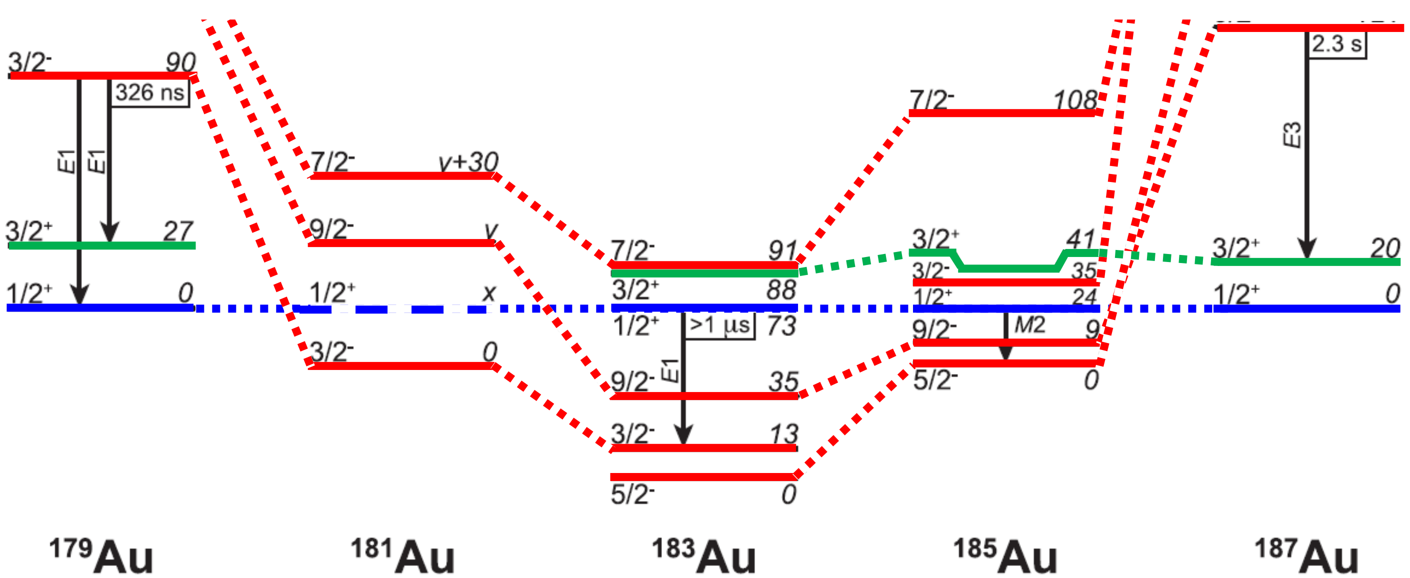
- **$^{180-182}$Au- stay strongly deformed**
- ^{176g,m,177m,g,179}Au – trend towards sphericity
- ^{178g,m}Au – both isomers are deformed
- J.G. Cubiss *et al.*, Phys. Rev. Lett. **131**, 202501 (2023)

Gold radii (Z=79)





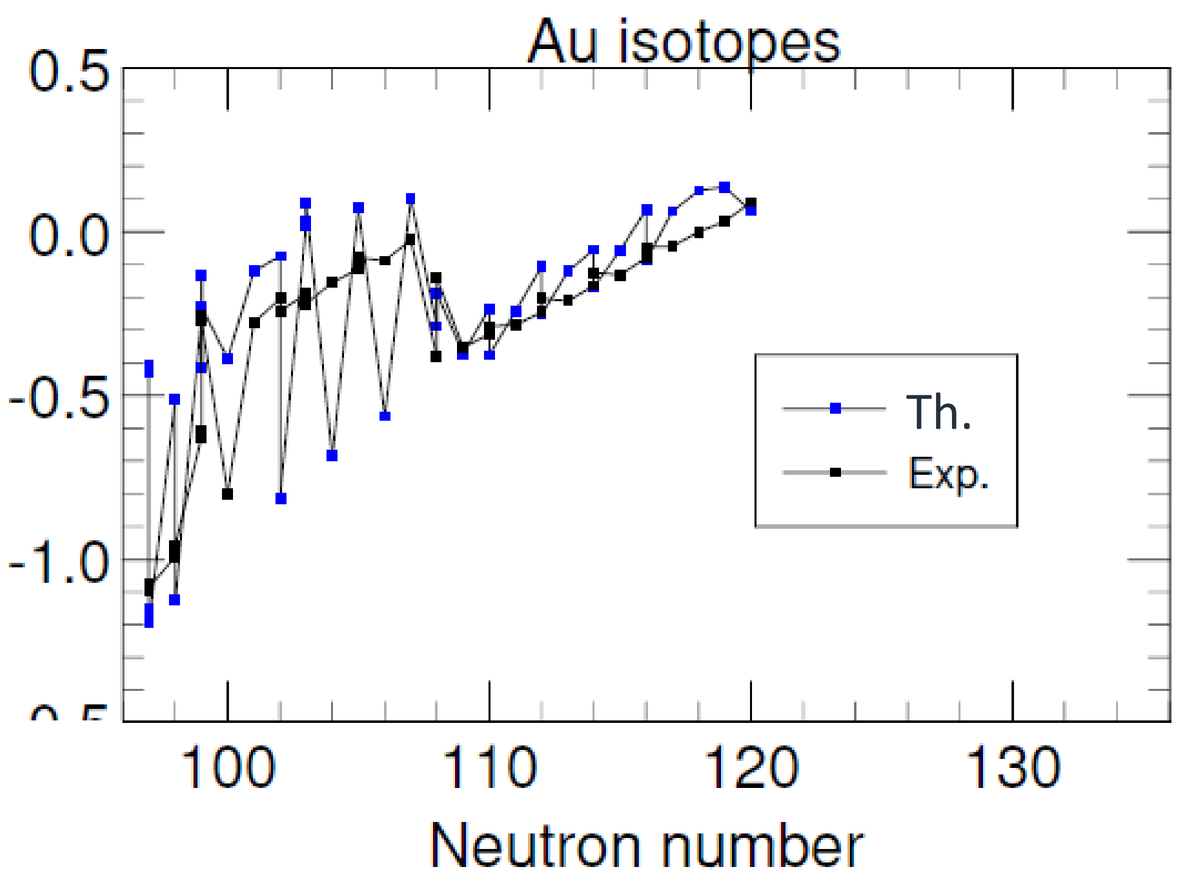
Heyde and Wood, Rev. Mod. Phys. **83**, 1467-1521 (2011)

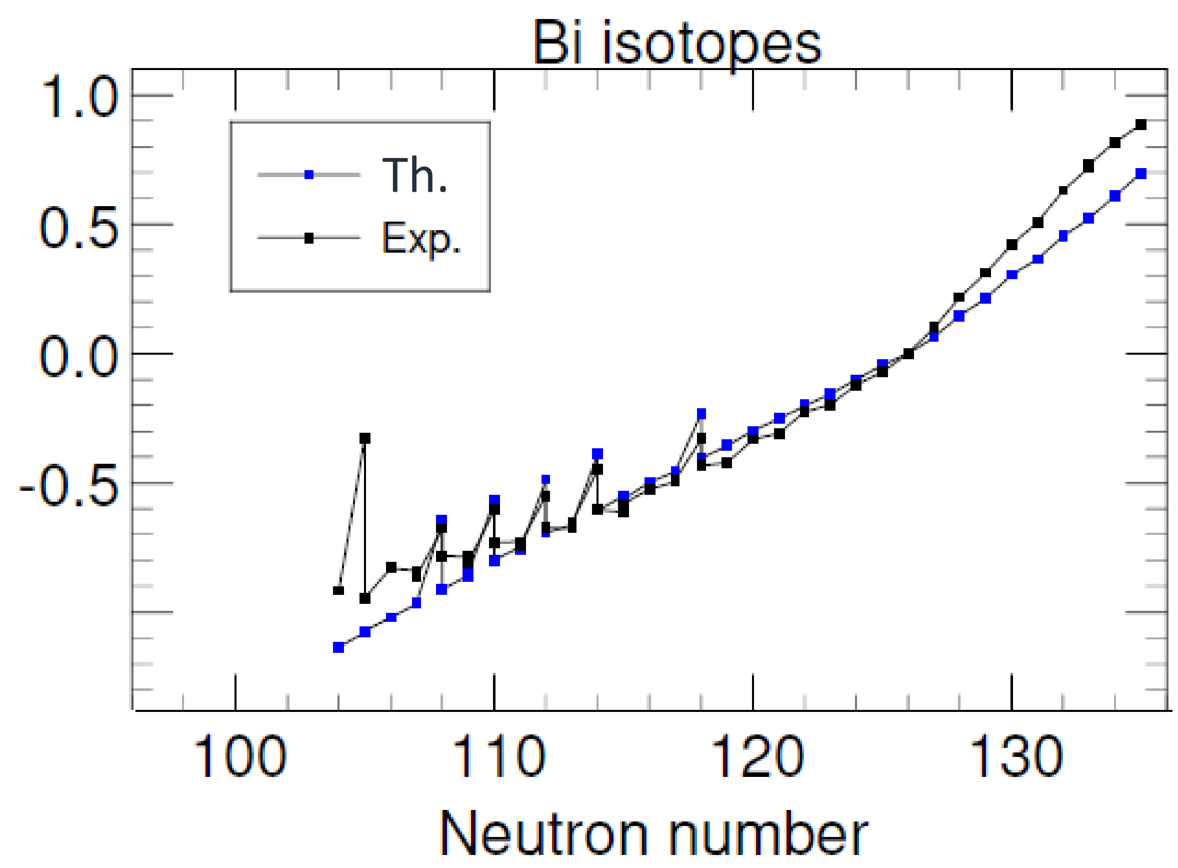


M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)

HFB calcs.: odd-A and odd-odd nuclei

- Odd-A, and particularly odd-odd nuclei are a challenge for theory
- HFB using D1M-Gogny (S. Goriely *et al.*, PRL **102**, 242501 (2009).).
- Begin by selecting states with correct spin, and calculating ground state.





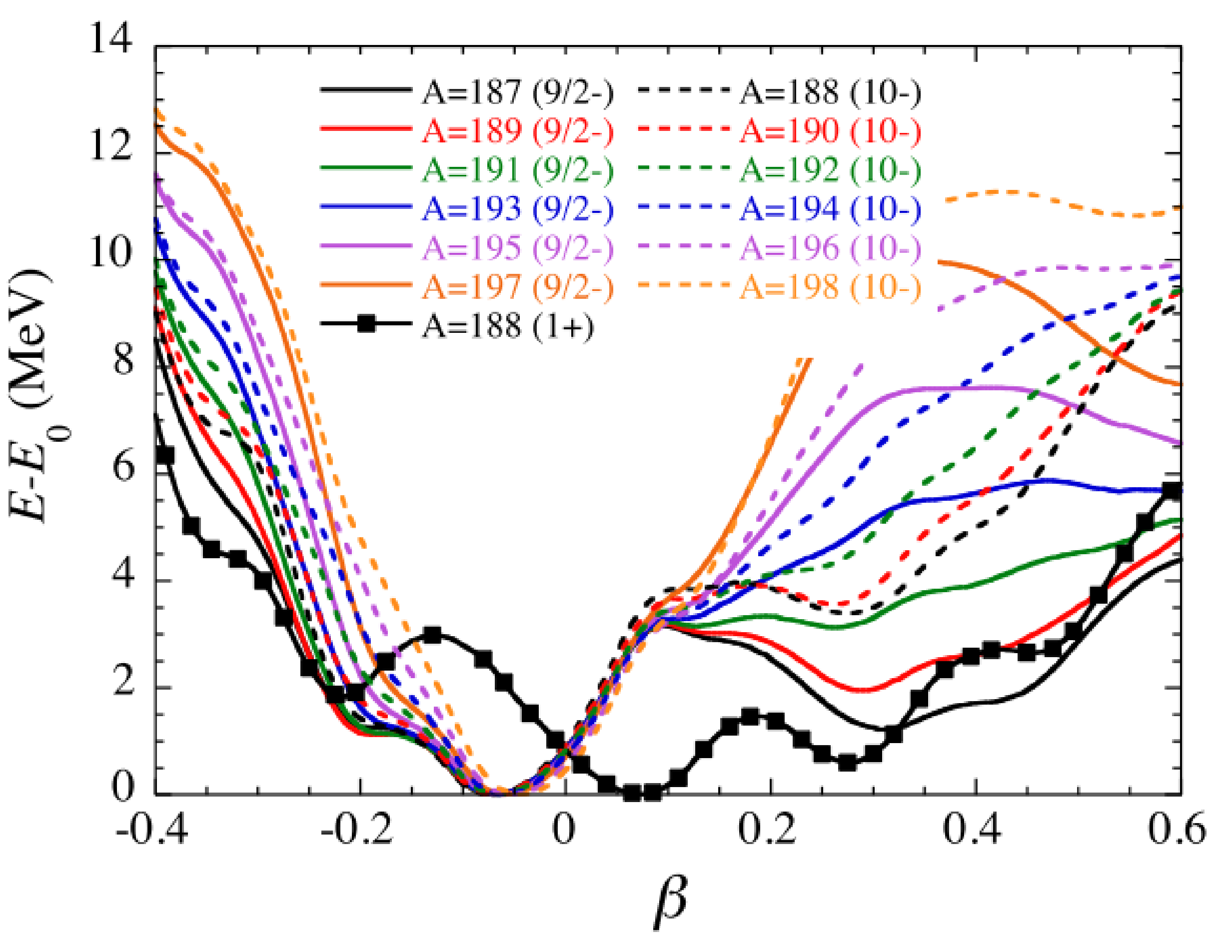
HFB for Bismuth

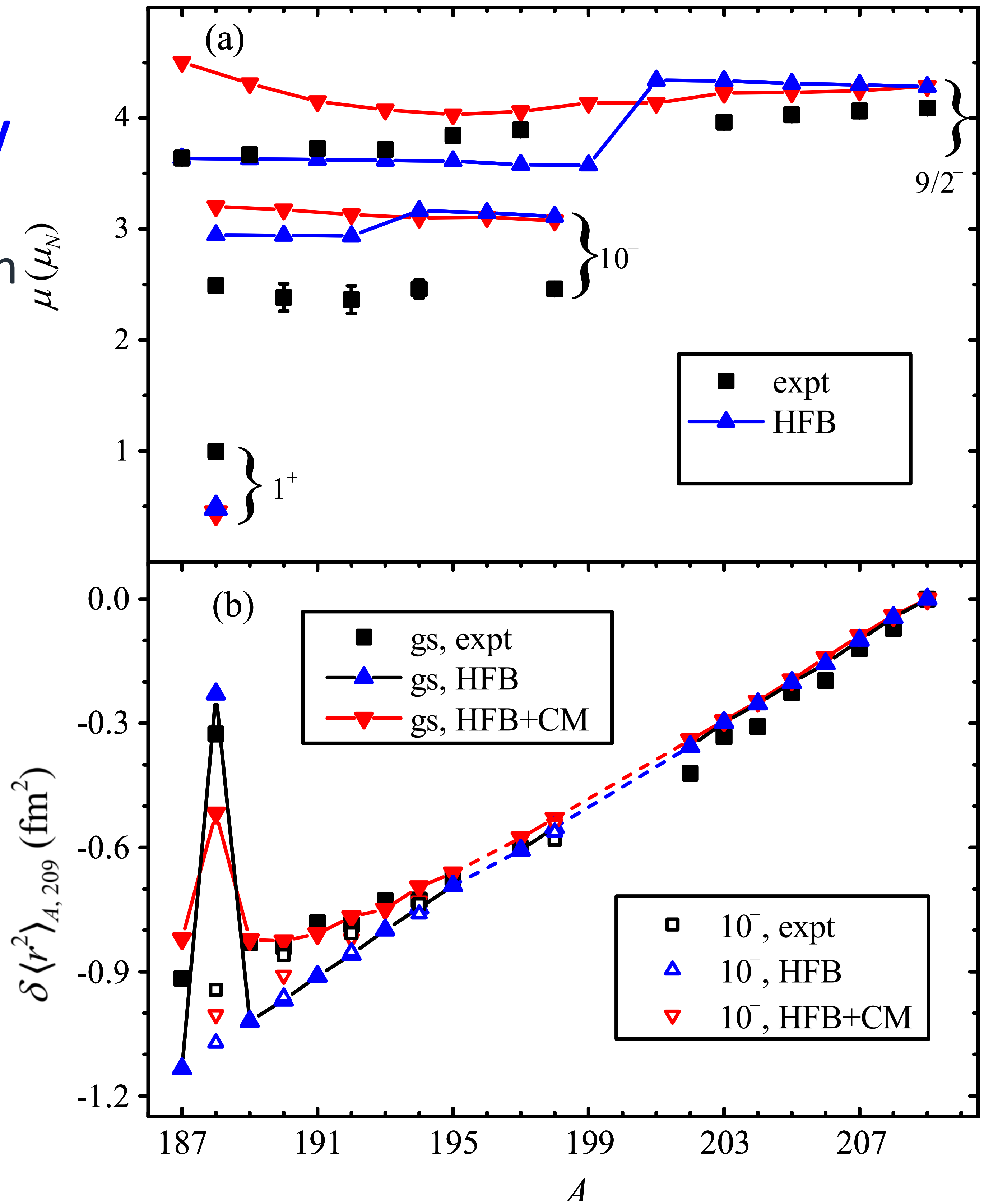
A.E. Barzakh *et al.*, PRL **127**, 192501 (2021)
S. Péru *et al.*, PRC **104**, 024328 (2021)

- Candidate states were selected by:
  Correct spin, agreement with μ, <1 MeV

- **Configuration mixing** across deformation surface introduced:

$$\langle \mathcal{O} \rangle = \frac{\int_q \mathcal{O} \exp(-E/T) dq}{\int_q \exp(-E/T) dq}$$

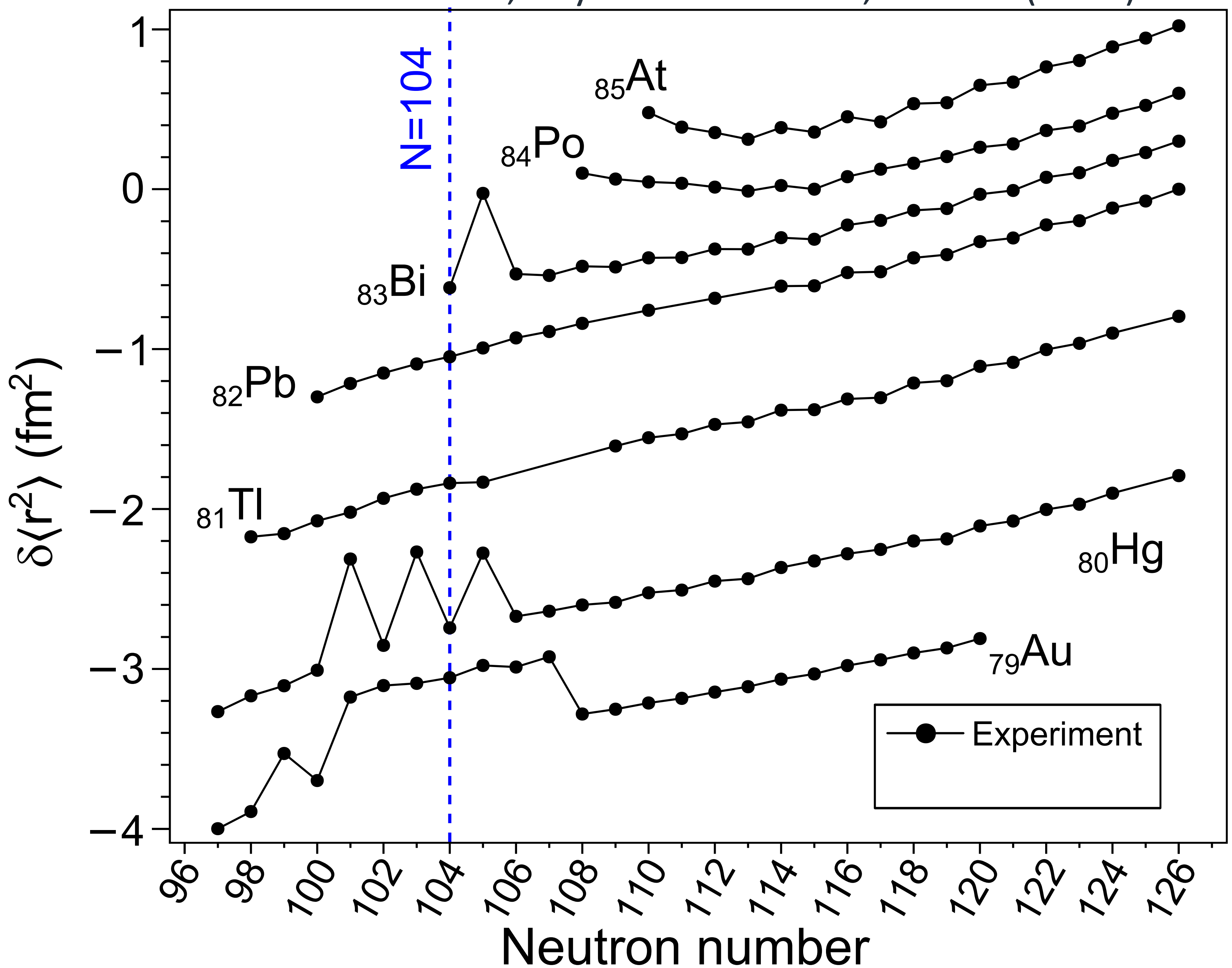




Charge-radii across the lead region, from Au to At (Z=79 to 85)

- Try applying same approach to proton-rich ground states of all chains we have measured (Z=79-85, ≈160 isotopes)
- All results here include mixing, using same statistical approach

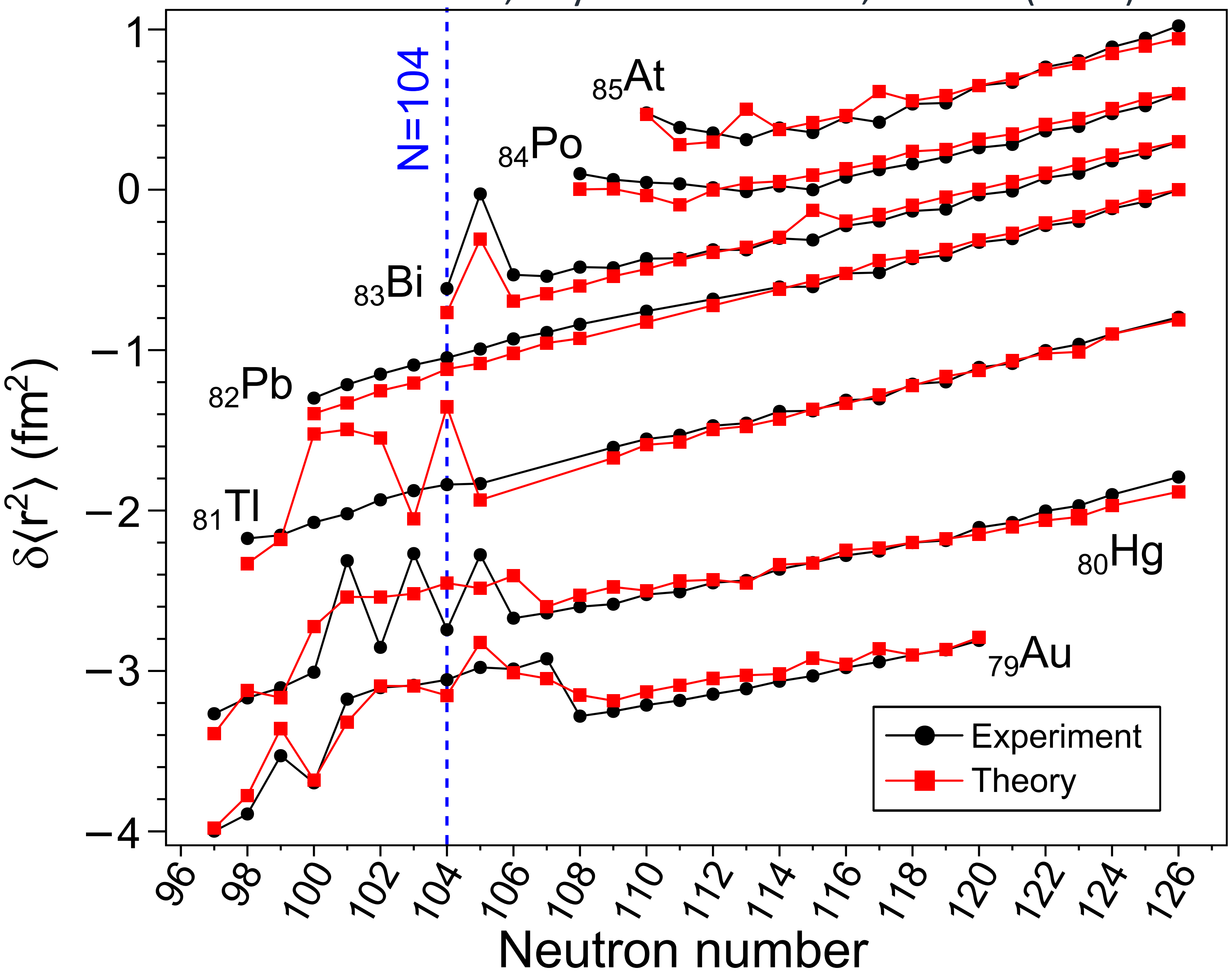
J.G. Cubiss *et al.*, Phys. Rev. Lett. **131**, 202501 (2023)



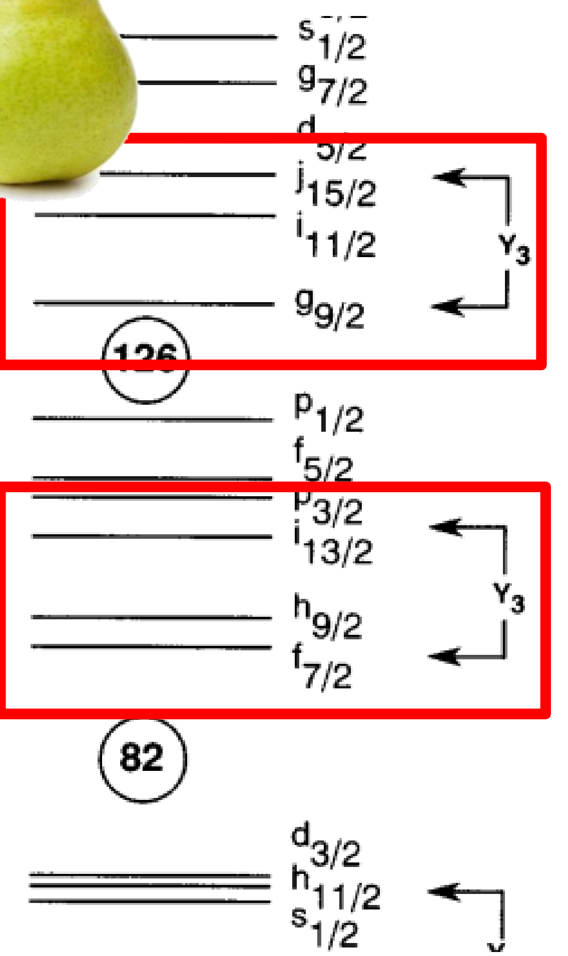
Charge-radii across the lead region, from Au to At (Z=79 to 85)

- Try applying same approach to proton-rich ground states of all chains we have measured (Z=79-85, ≈160 isotopes)
- All results here include mixing, using same statistical approach
- Exceptions in Tl and Hg chain:
    - Tl, more deformed state with better match with moment (by fractions to couple of %)
    - Hg, only reproducible by selecting correct sign of deformation

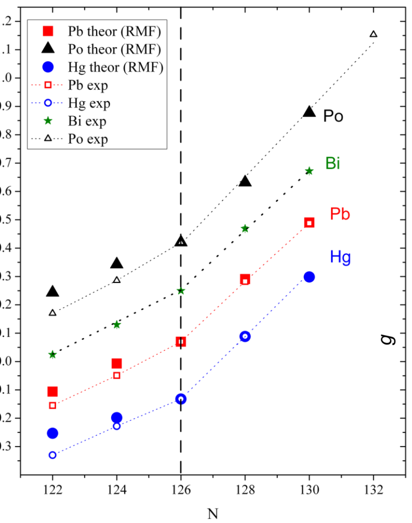
J.G. Cubiss *et al.*, Phys. Rev. Lett. **131**, 202501 (2023)

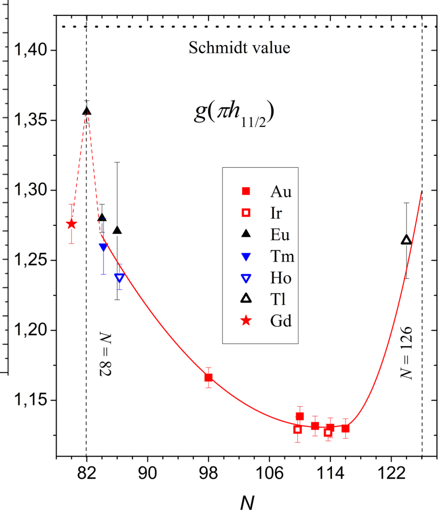


Recent results and future possibilities

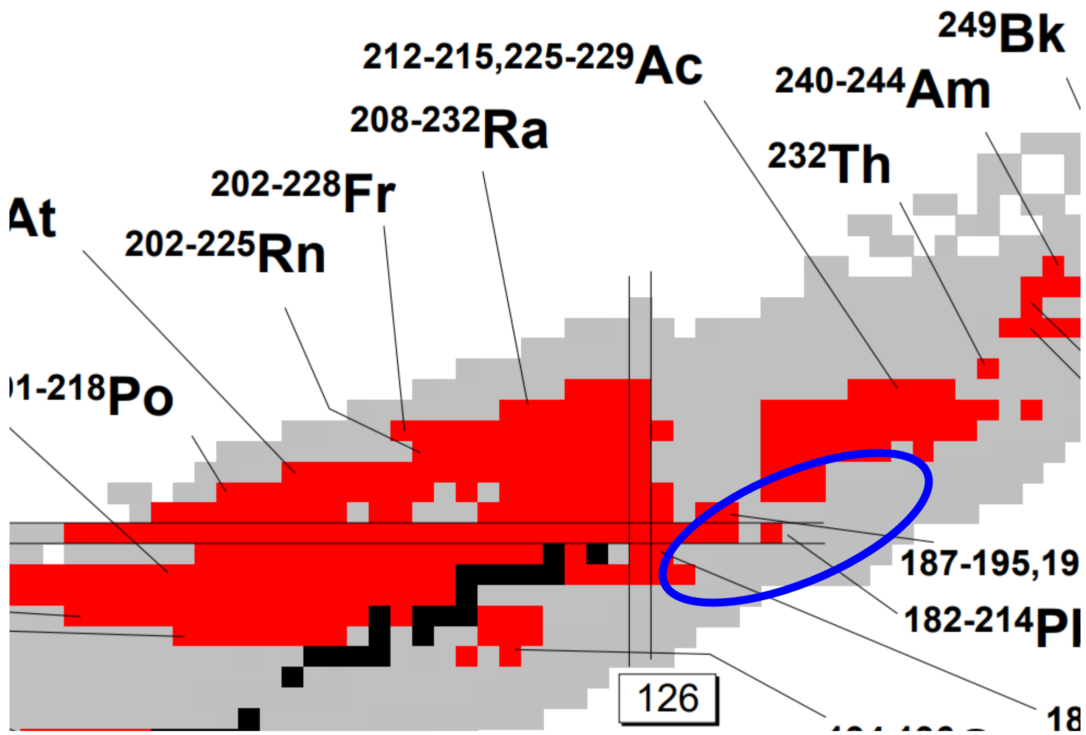


Shell effects





[Laser Spectroscopy – Institute for Nuclear Physics – TU Darmstadt (tu-darmstadt.de)]

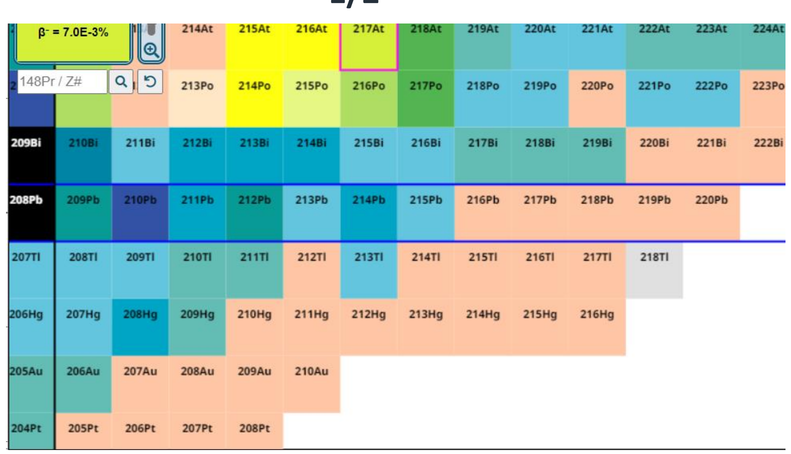


See also, for example:
P.L. Sassarini *et al.*, J. Phys. G **49**, 11LT01 (2022)
A.R. Vernon *et al.*, Nature **607**, 260-265 (2022)
R.P. de Groote *et al.*, PLB **848**, 138352 (2024)
J. Dobaczewski's talk (Thurs. 14:00)

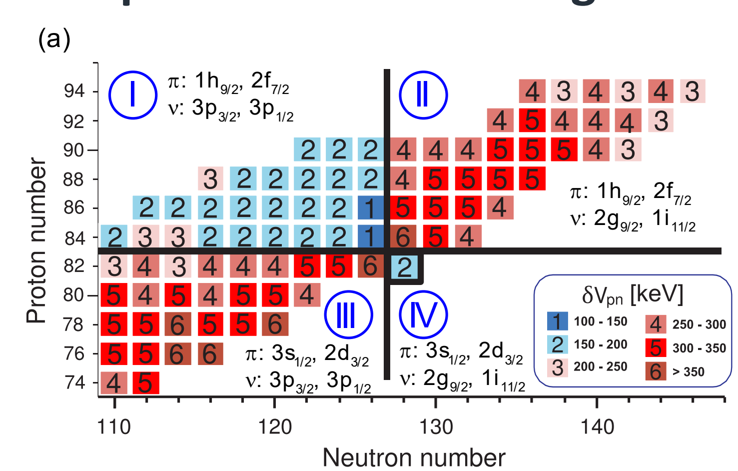
Decay properties and masses – unexplored territory

Energy 1st excited state

Ground state $T_{1/2}$

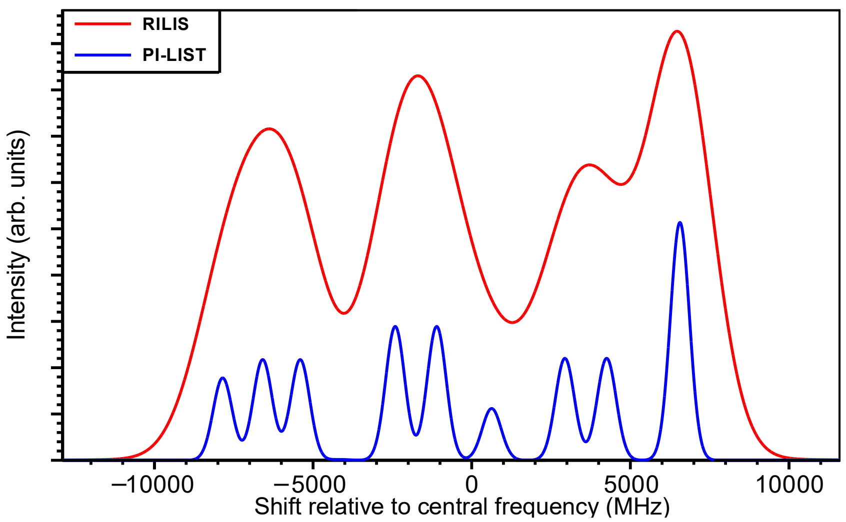


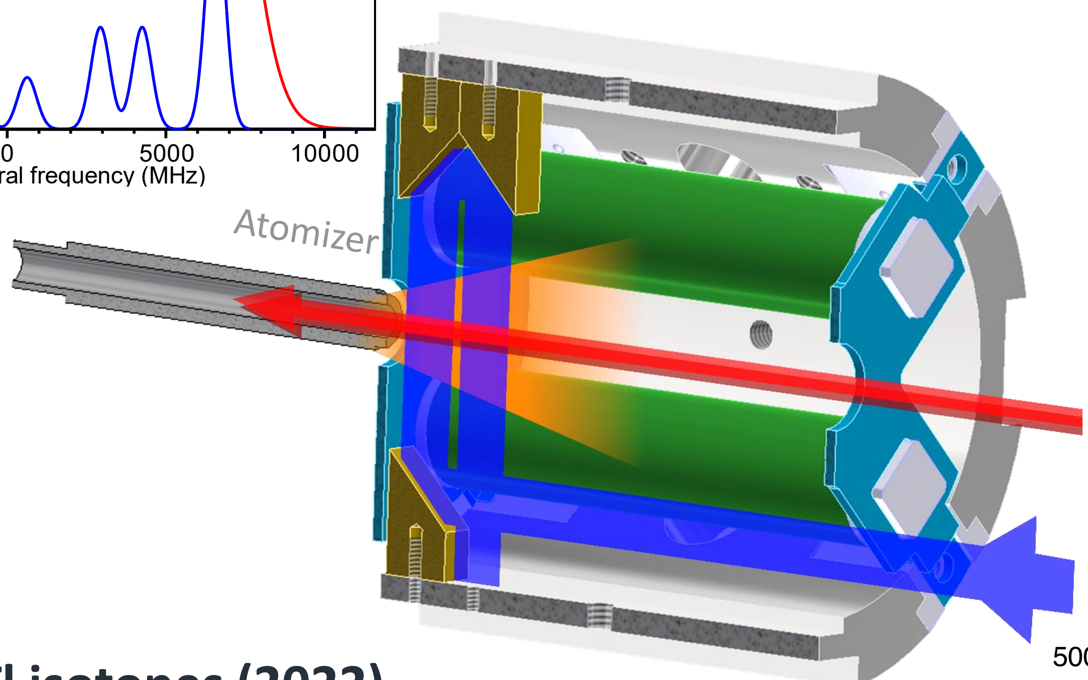
Last p-n interaction strength



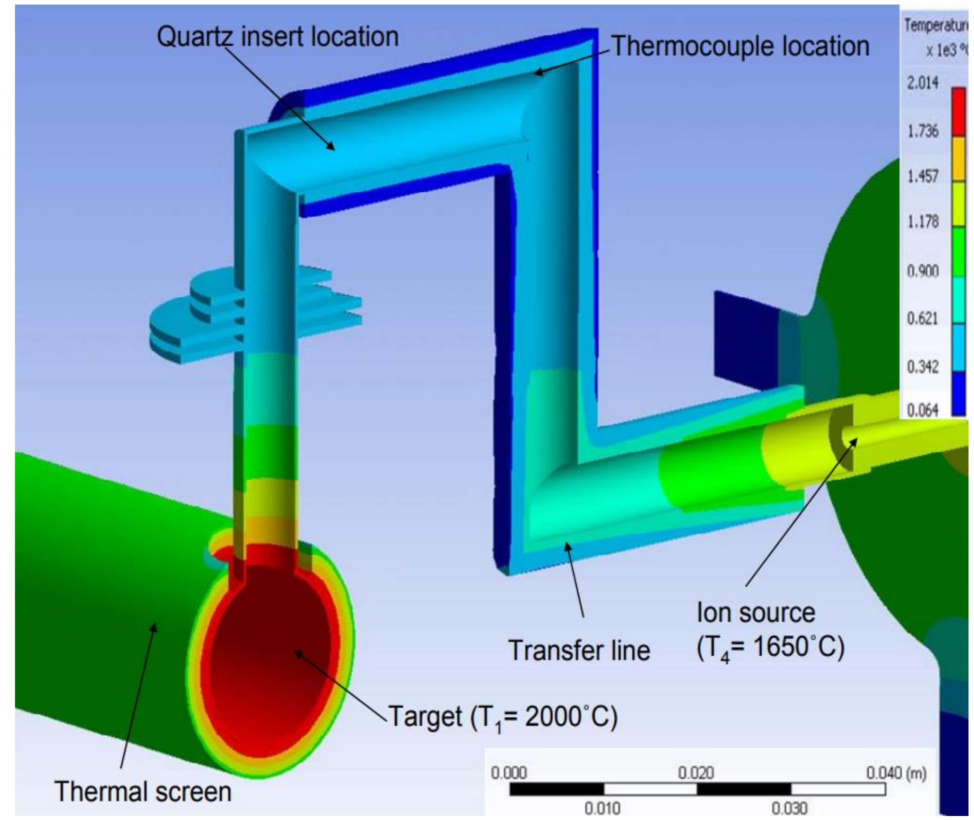
The LIST and quartz lines

R. Heinke *et al.*, *Hyperfine Interactions* **238**, 6 (2017)

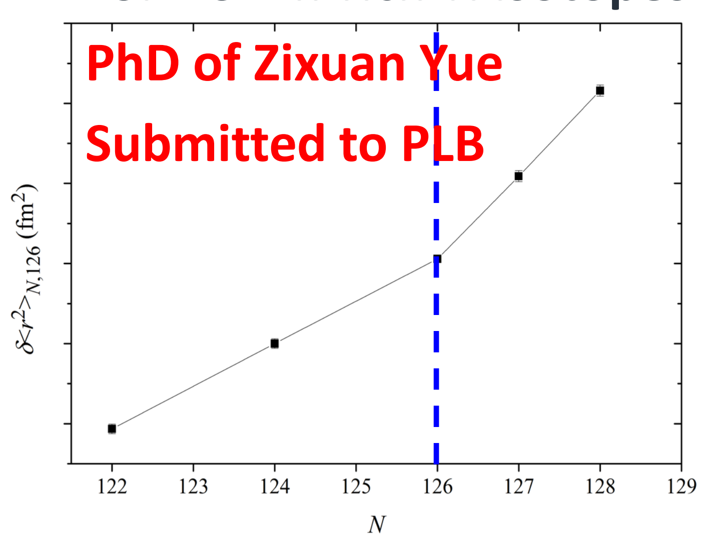


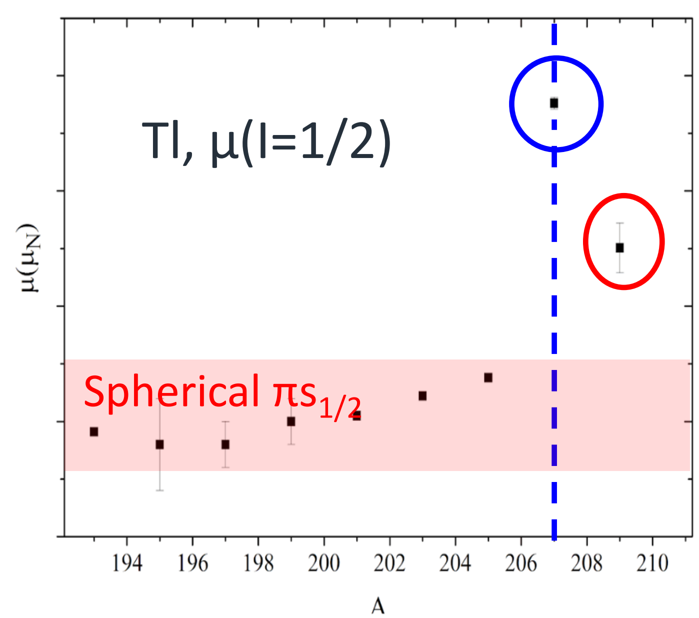


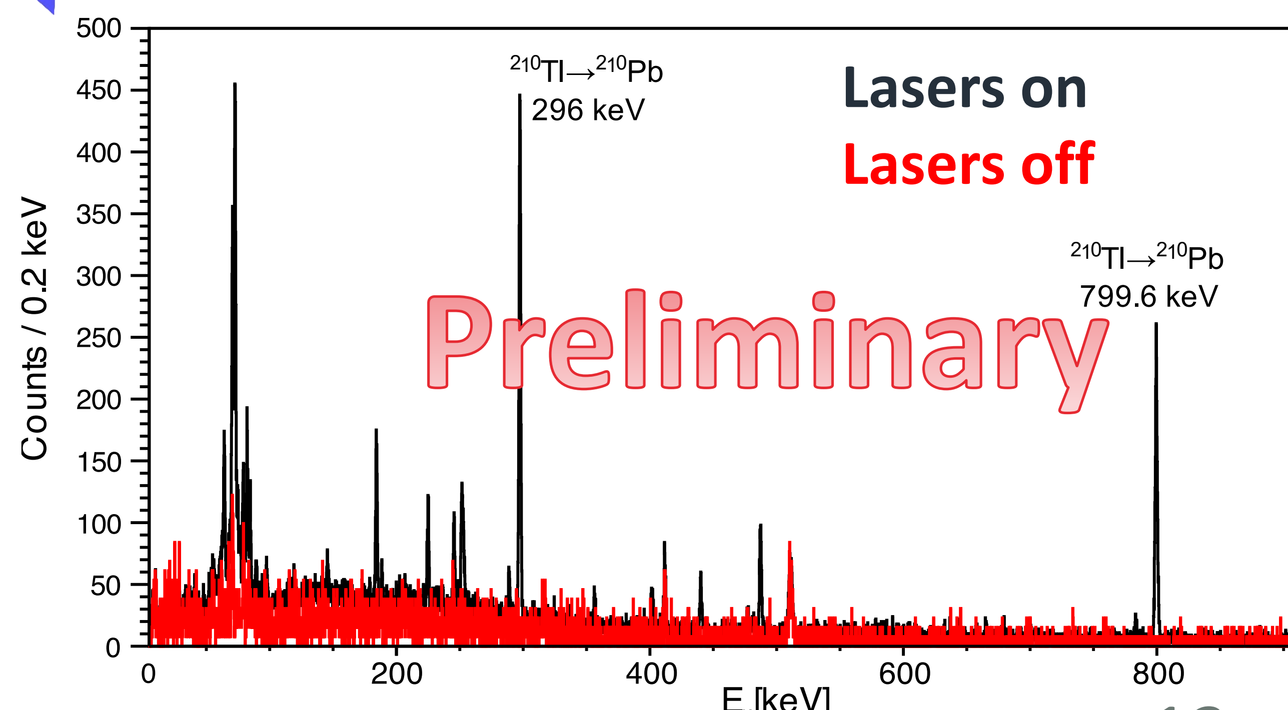
LoI244 – n-rich Hg isotopes (2023)



LoI219 – n-rich Tl isotopes (2022)





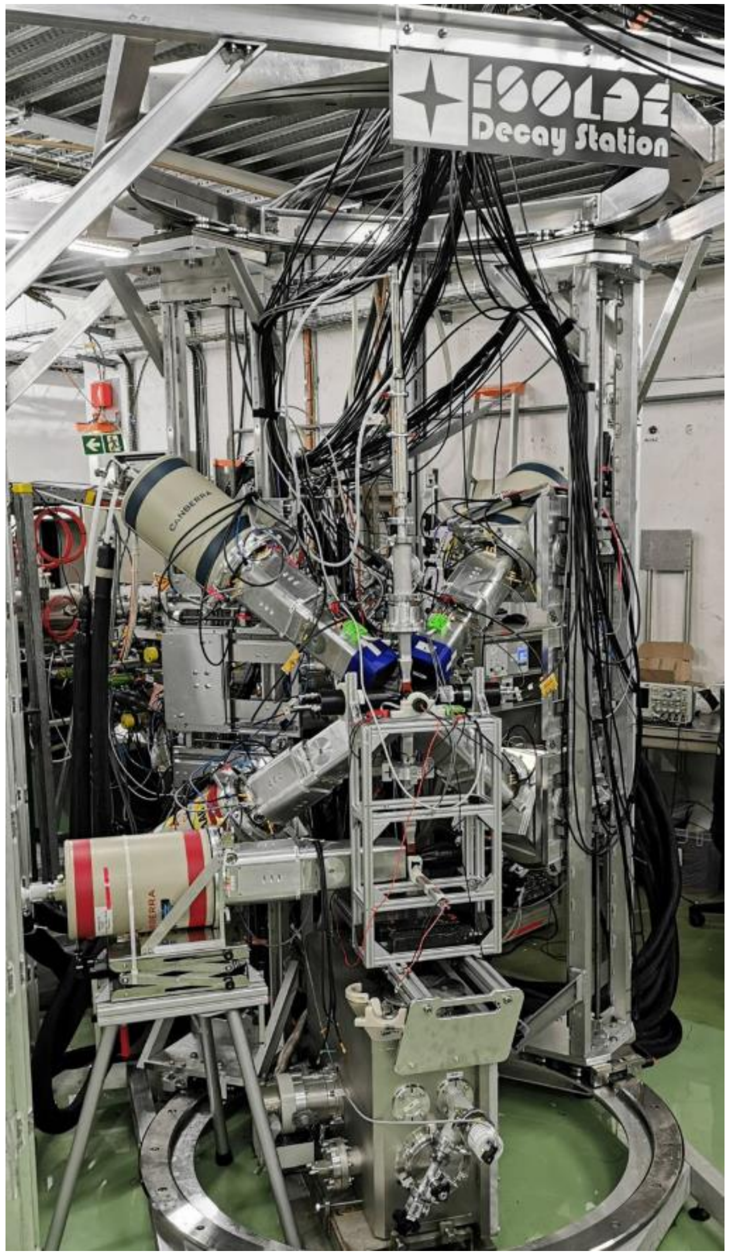


Sensitivity boost

Past - Windmill

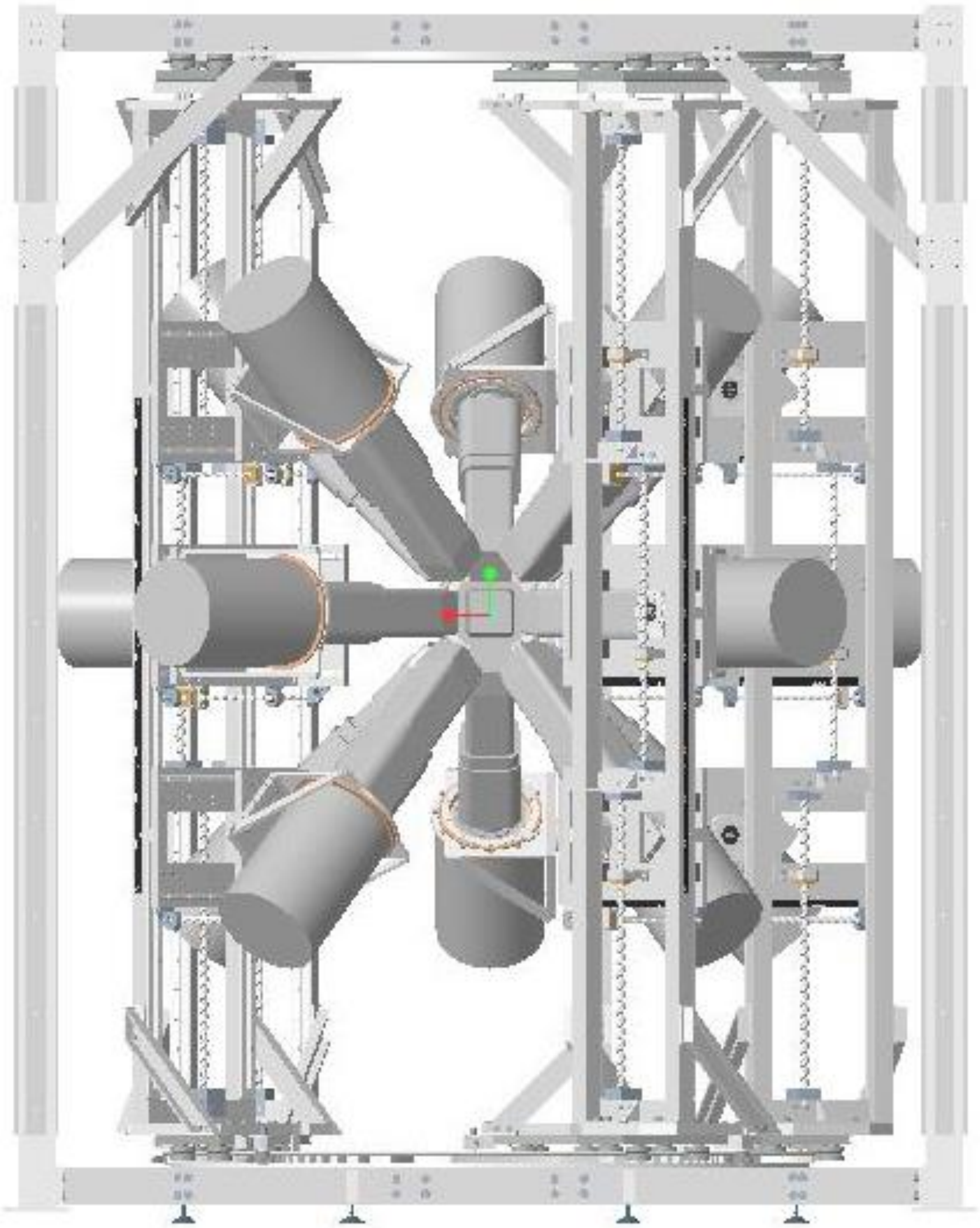
- **1 planar germanium**
- 2(+2) Silicons
- 1(+1) Germanium

Present - IDS



- **6 germanium clovers (24 crystals)**
- Plastics for beta tagging ($\varepsilon = 30 - 40\%$)

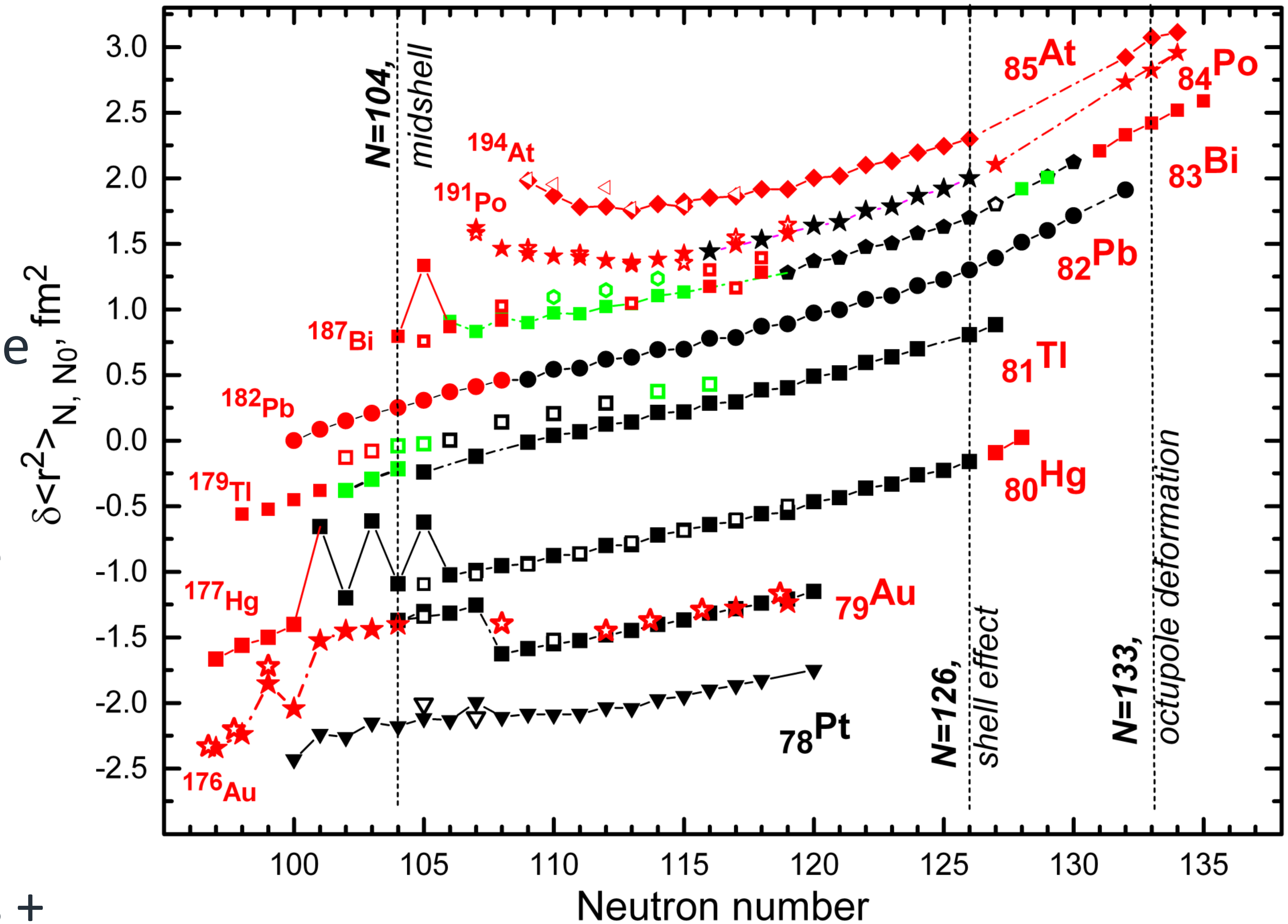
Future – "more" IDS



- **12(+3) clovers (up 60 crystals)**
- Even more plastic… (ε up to 70%)

Summary

- Wide ranging studies of charge radii in the lead region has been performed using in-source laser spectroscopy
- Calculations highlight the important role moments and radii can play in constraining models
- Ion source developments + increase in sensitivity open new possibilities for in-source spec.
- **More physics and more fun to come ☺!**



Red data = our data from ISOLDE campaign

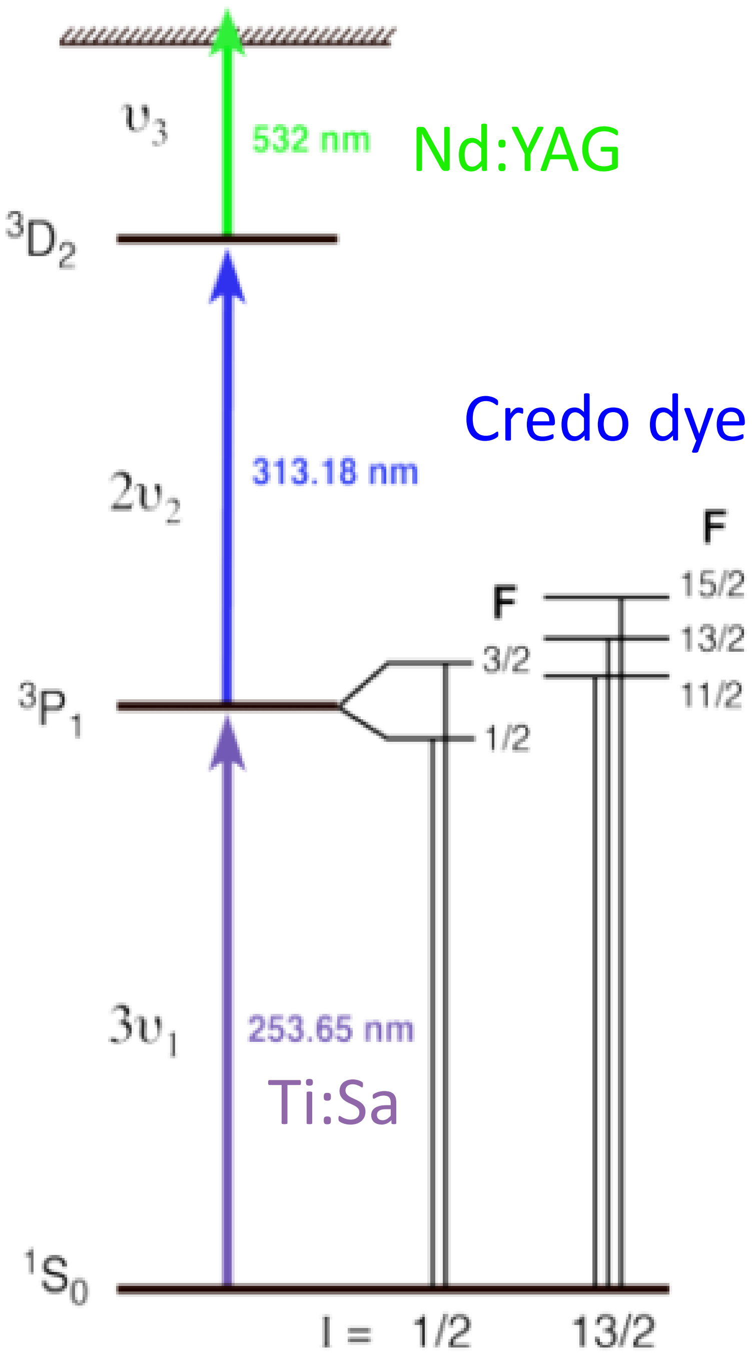
Green points = Gatchina

Black points = literature

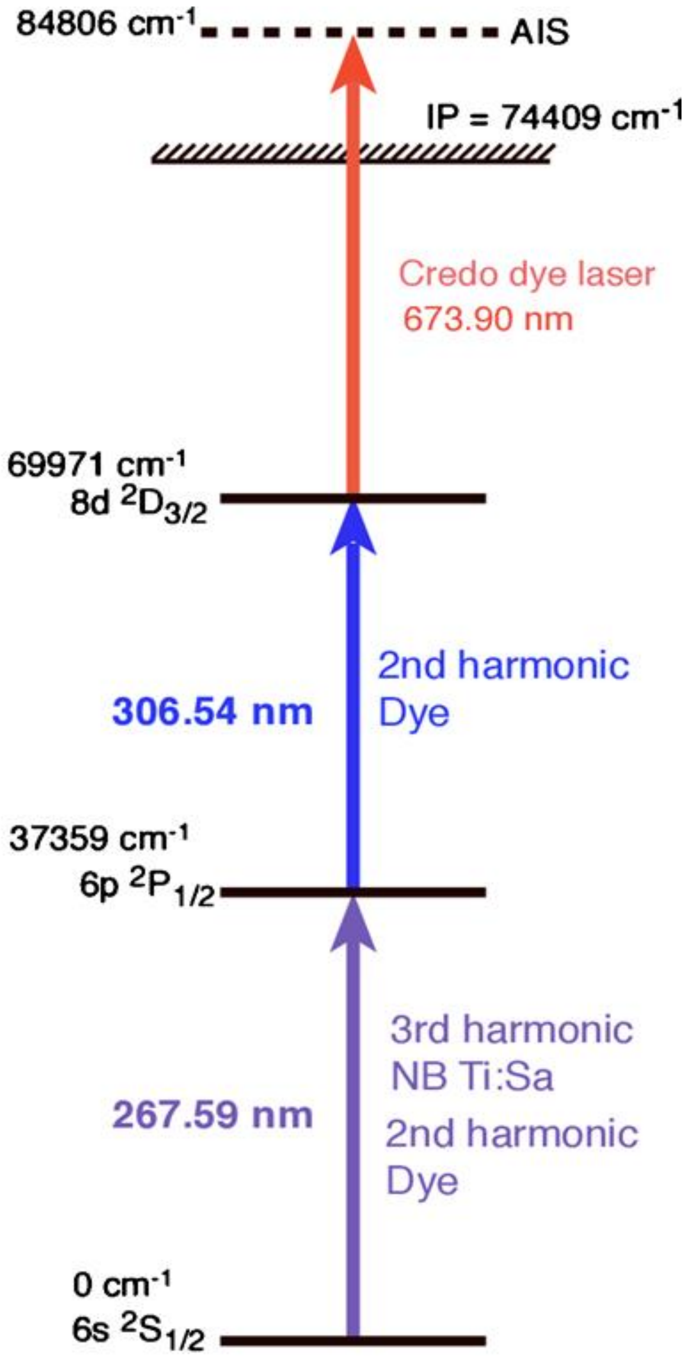
Thank you for listening

Additional slides

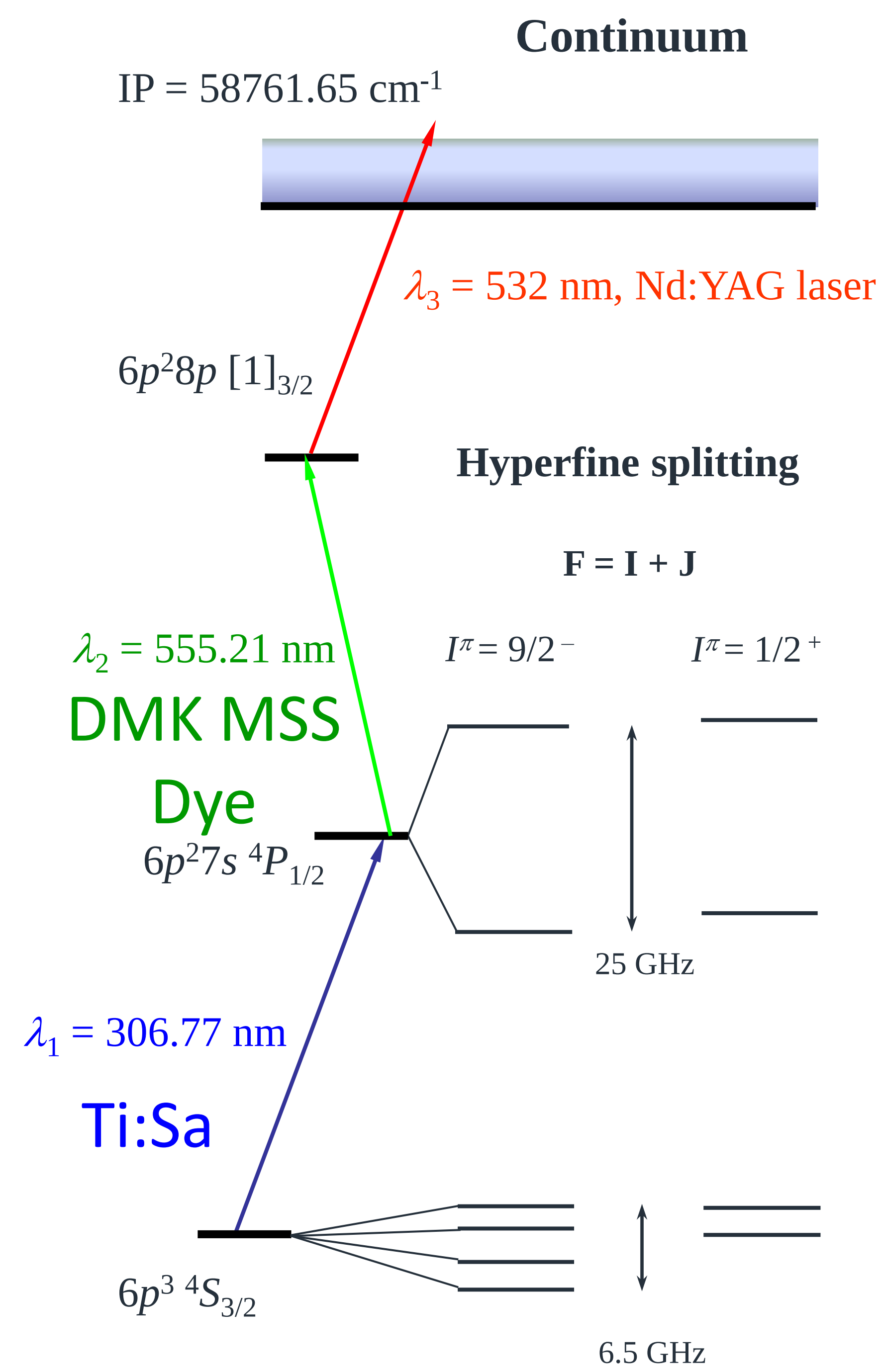
Ionisation schemes



Hg



Au



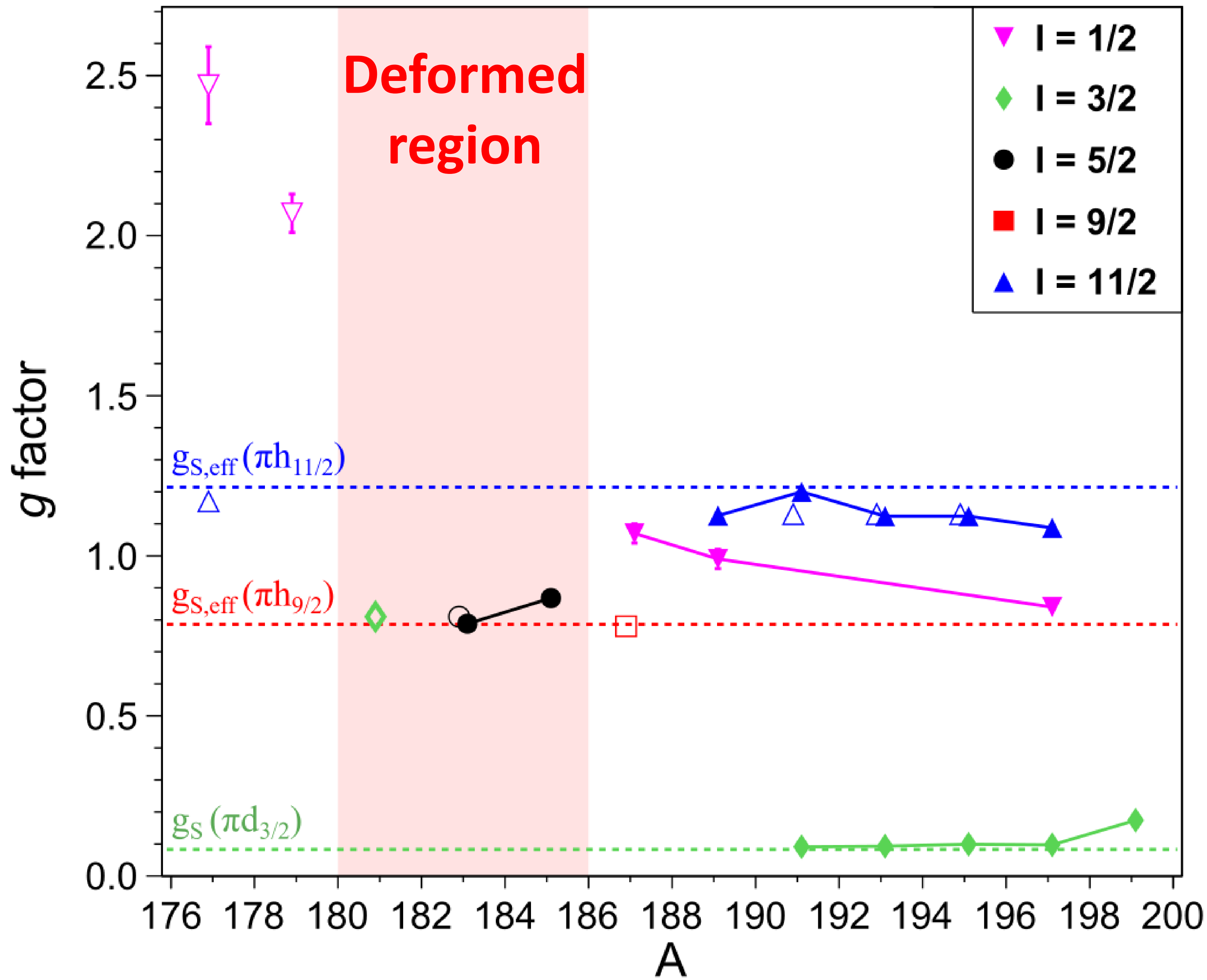
Bi

g factors of odd-A golds (guilty as charged)

- **Our data** – hollow symbols
  Literature – filled symbols

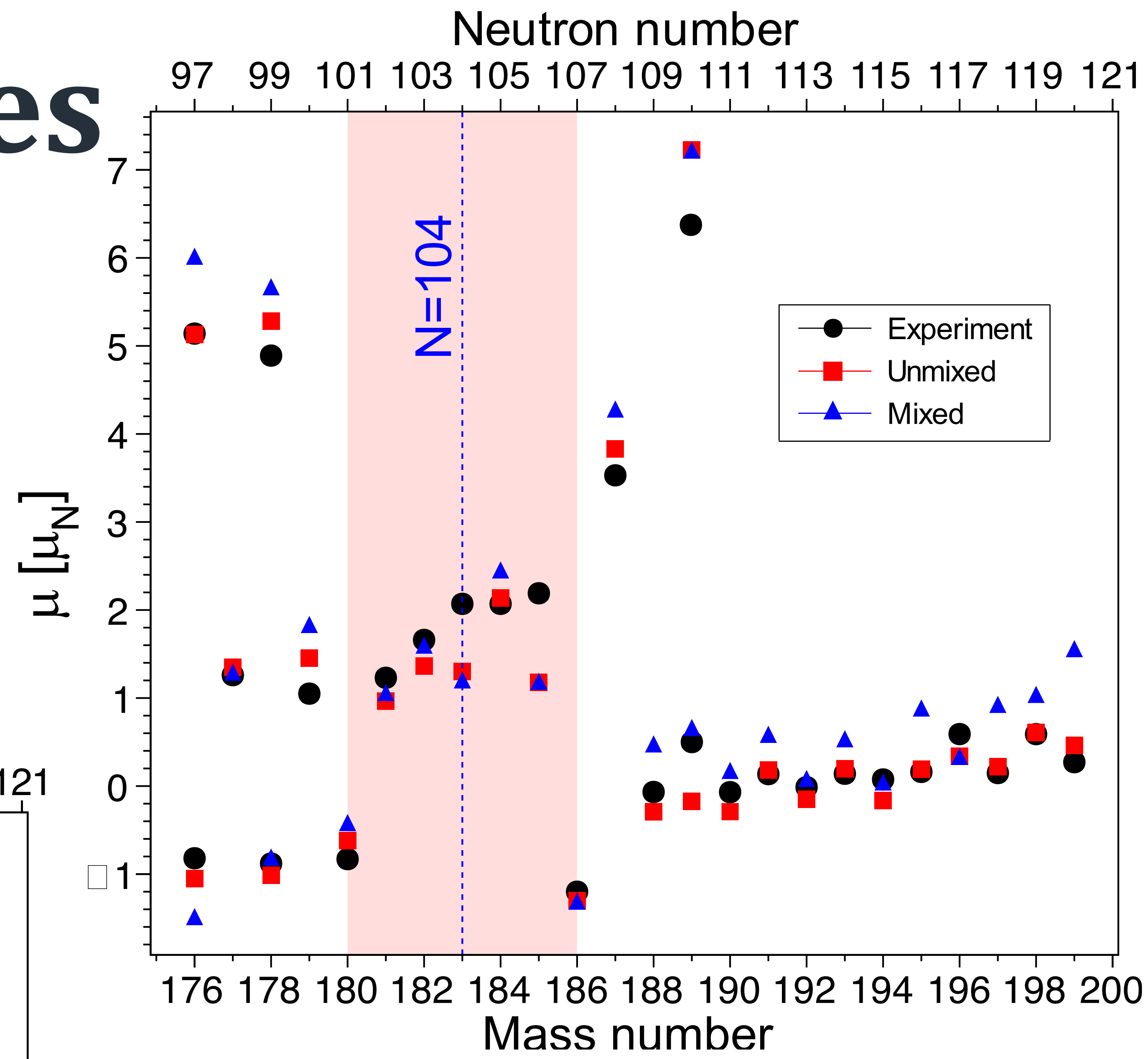
- Good agreement between:
  - Our and past data
  - Single-particle Schmidt estimates

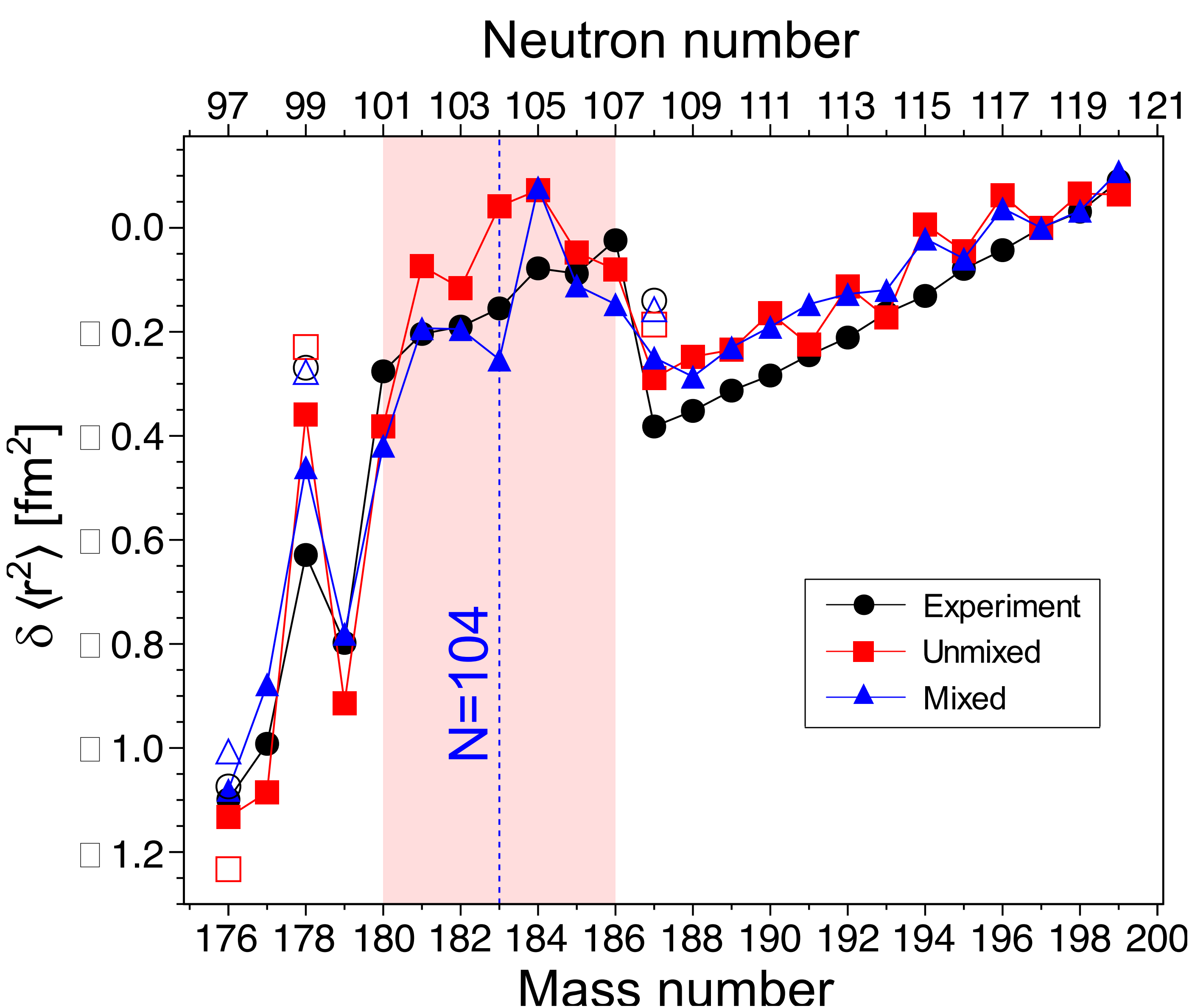
- Why effective g factor for $h_{9/2,11/2}$, but not $d_{3/2}$? Should be a consistent approach.



HFB for Au isotopes

- Try applying same approach as used in Bi isotopes both for **unmixed** and **mixed** cases
  States selected by spin, and dipole moment

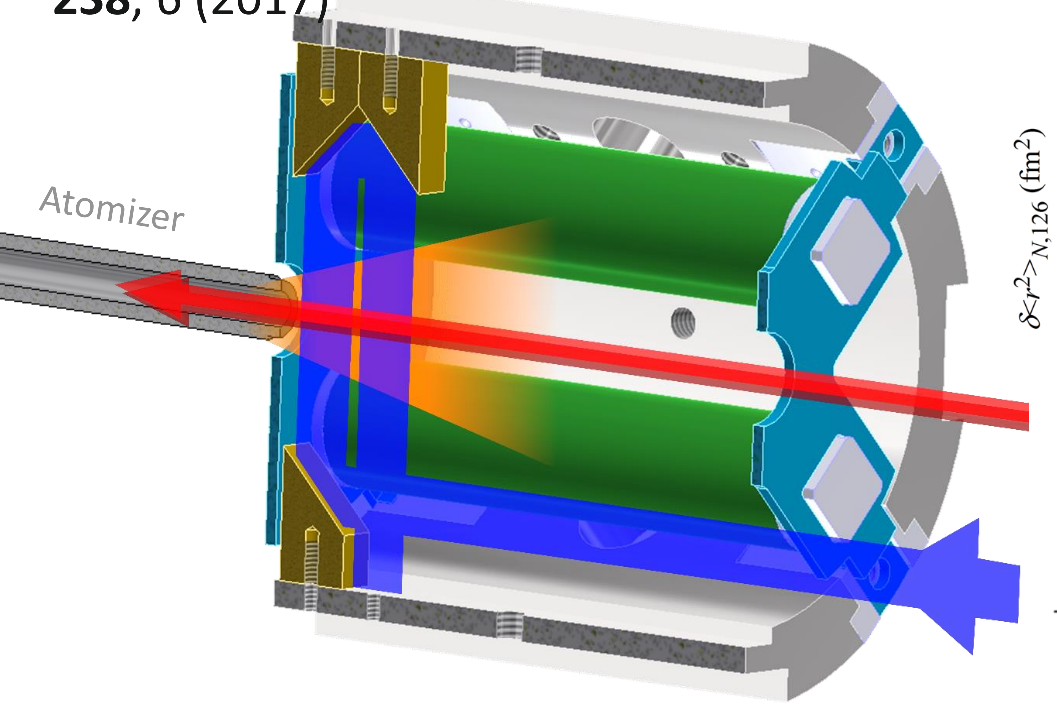


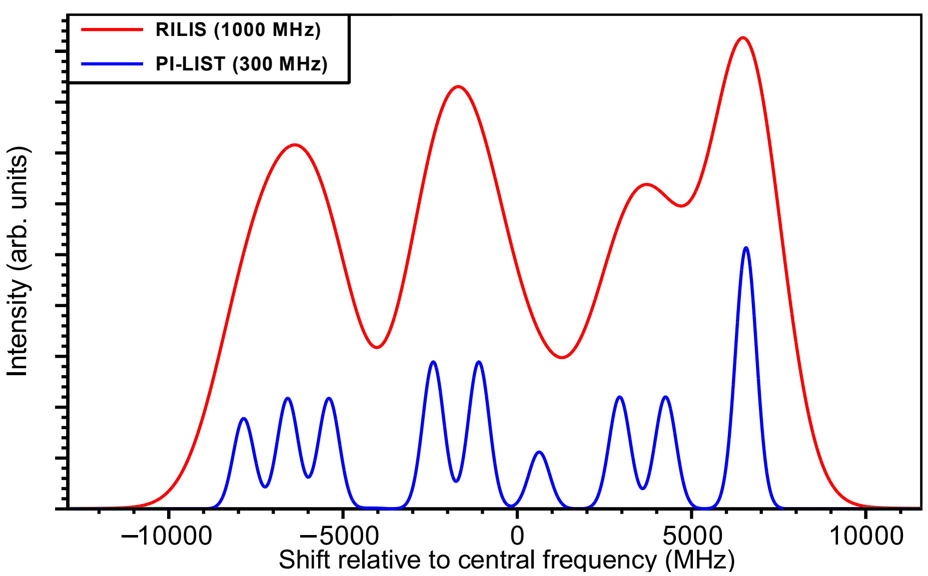


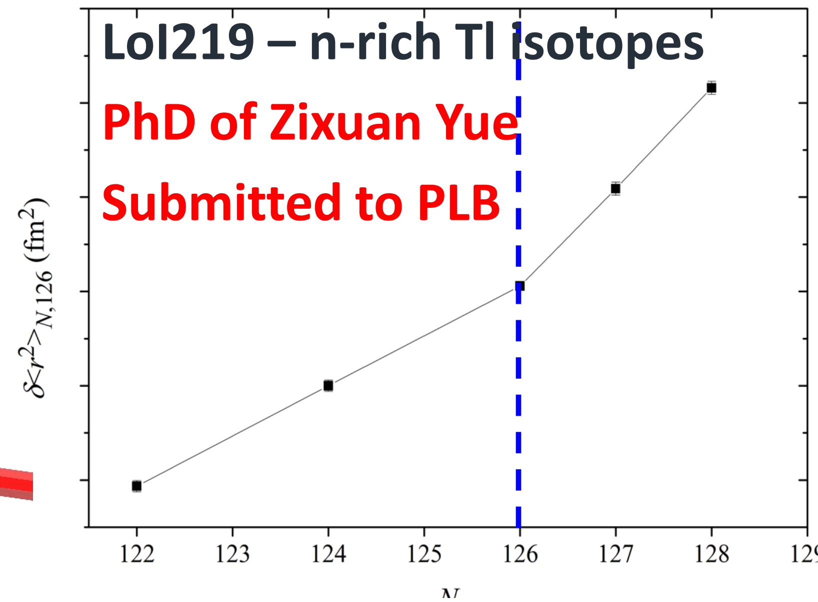
- A good agreement with experiment is seen
- Inclusion of mixing gives similar results

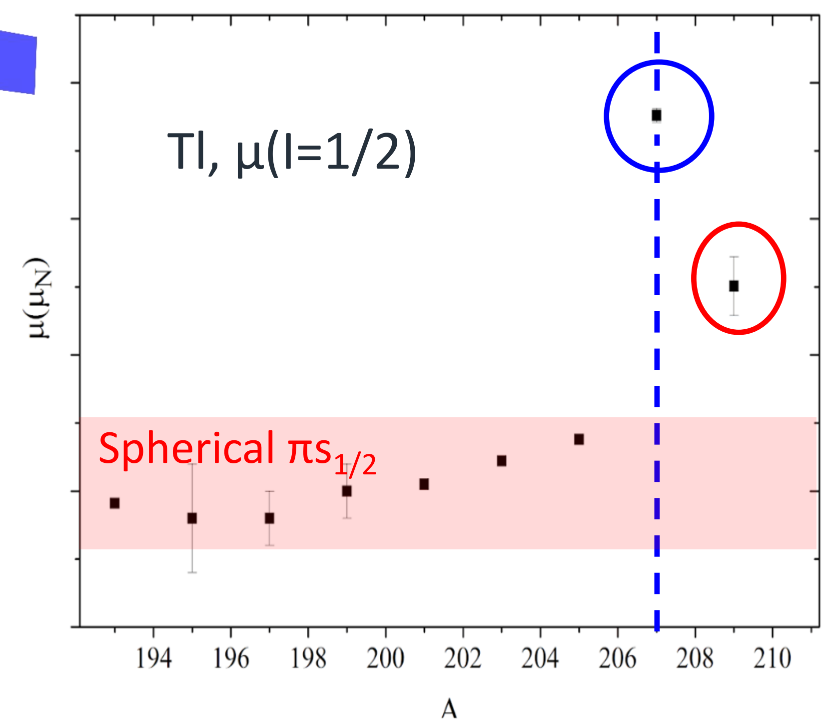
The Laser Ion Source and Trap

R. Heinke *et al., Hyperfine Interactions* **238**, 6 (2017)

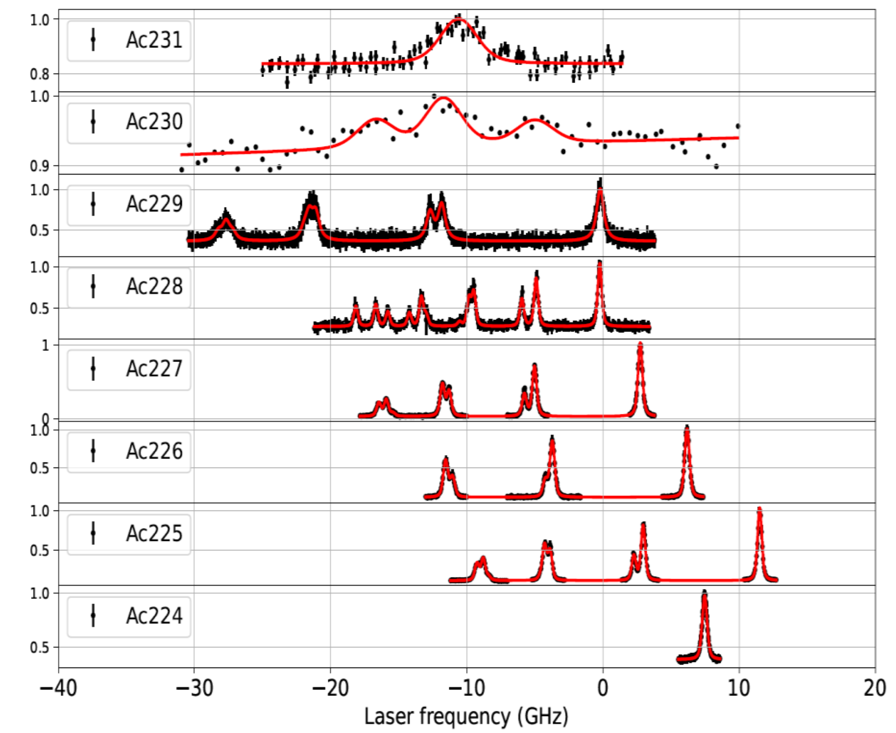




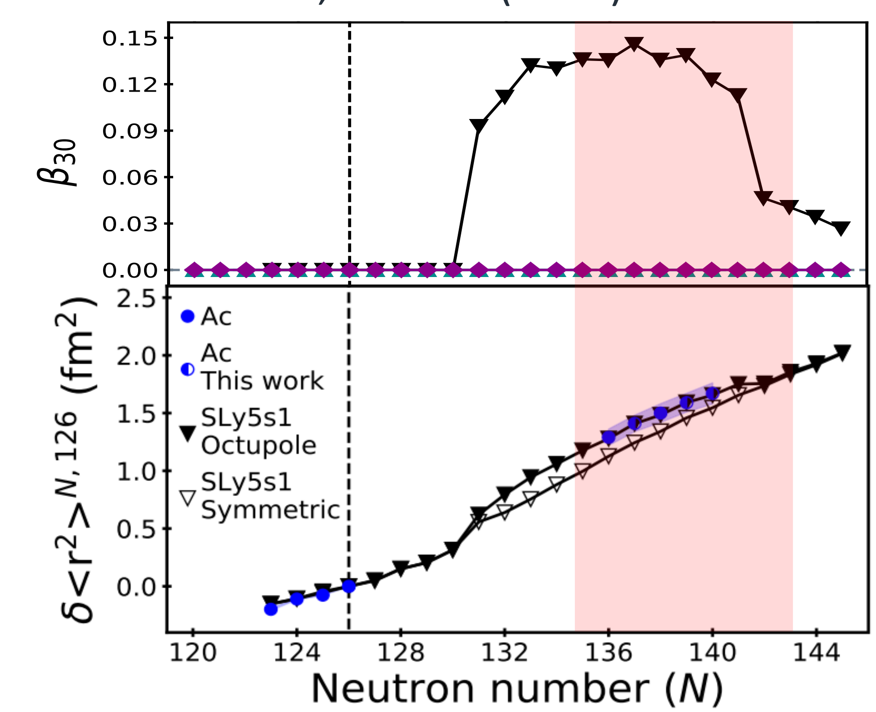




LoI 216 – Actinium isotopes



E. Verstraelen *et al.*,
PRC **100**, 044321 (2019)

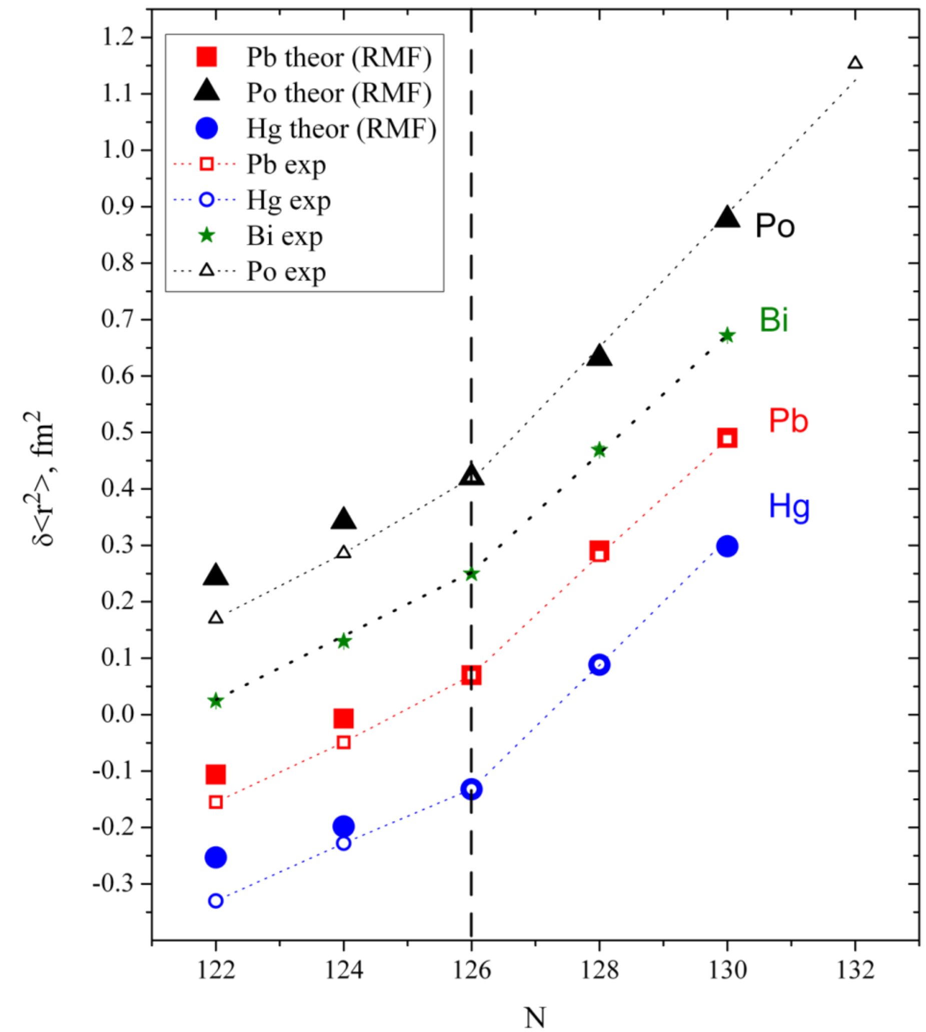


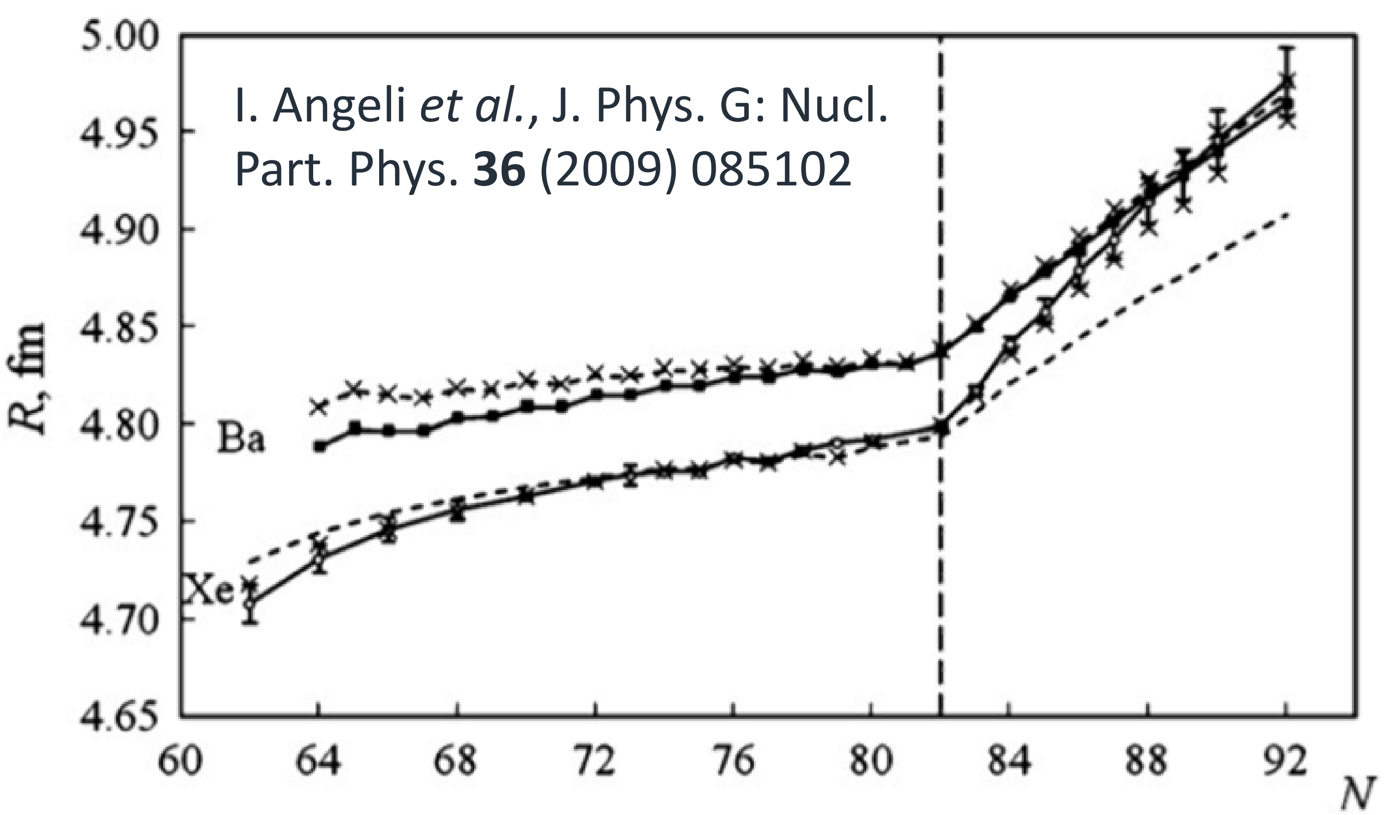
Operation mode	Mode loss factor	Combined loss factor	Est. total efficiency (%)
Standard RILIS			10
LIST ion guide	3	3	3.3
LIST high purity	33	100	0.1
PI-LIST	2	200	0.05
PI-LIST opt.	10	2000	0.005

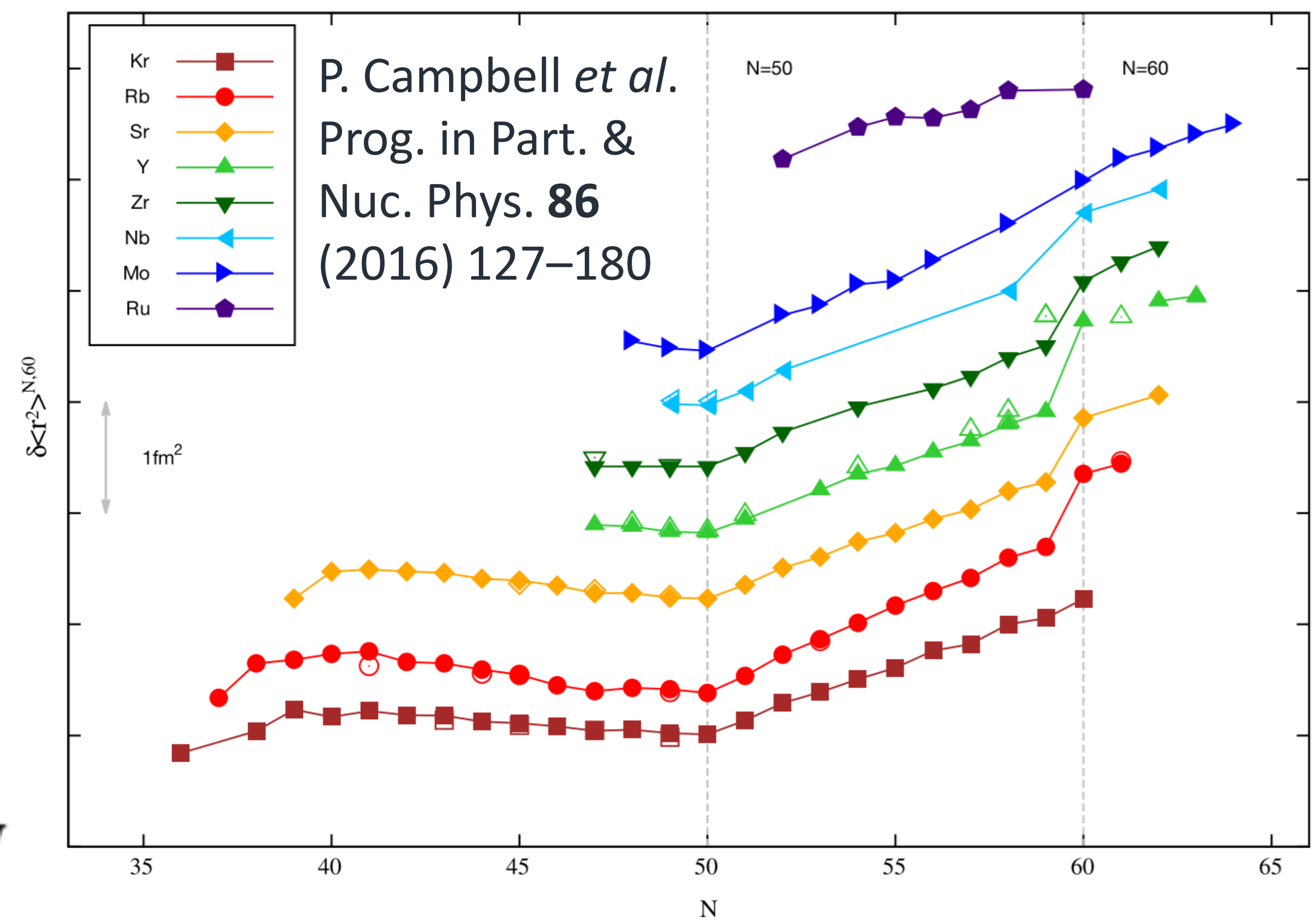
R. Heinke *et al., NIM,* **B541**, (2023) 8-12

“Kinky” shell effect

- Slope in $\delta\langle r^2\rangle$ increases when crossing a shell closure – seen all over nuclear chart
- Seen in elements above and below proton shell closures
- Effect is seen in both odd- and even-Z nuclei
- Also seen in both odd-Z and odd-N – not odd-even staggering!





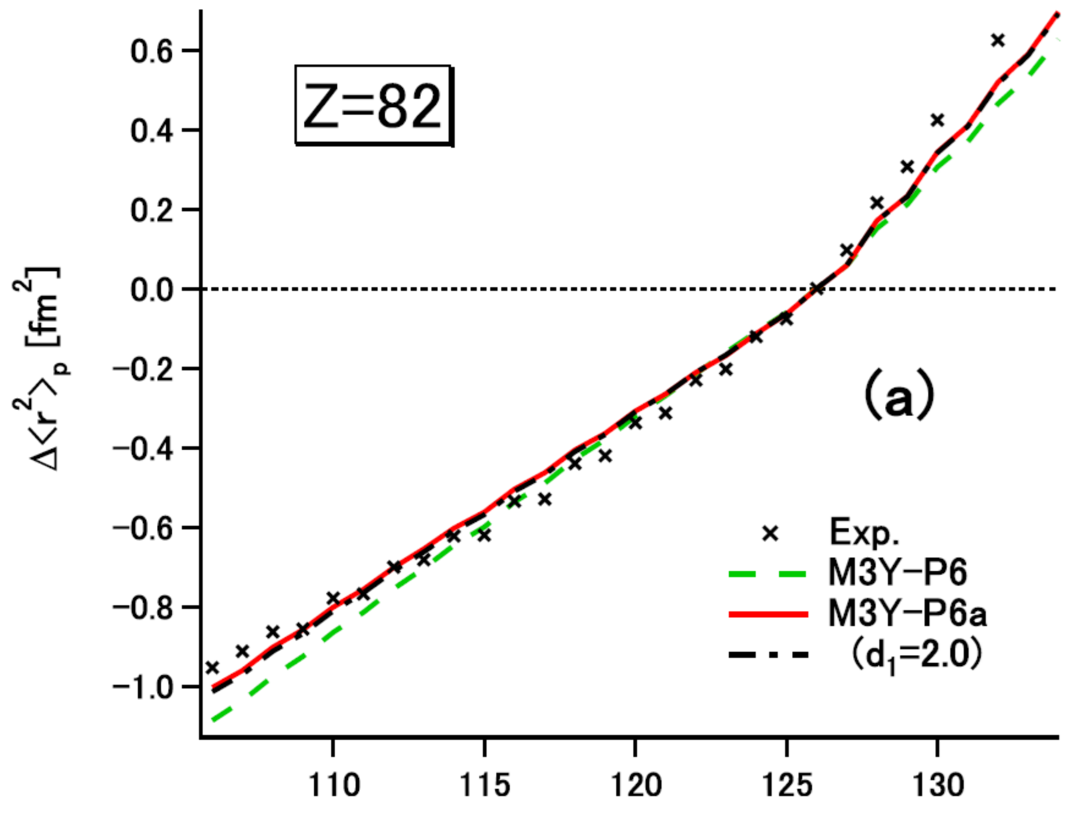


Theoretical description of kink

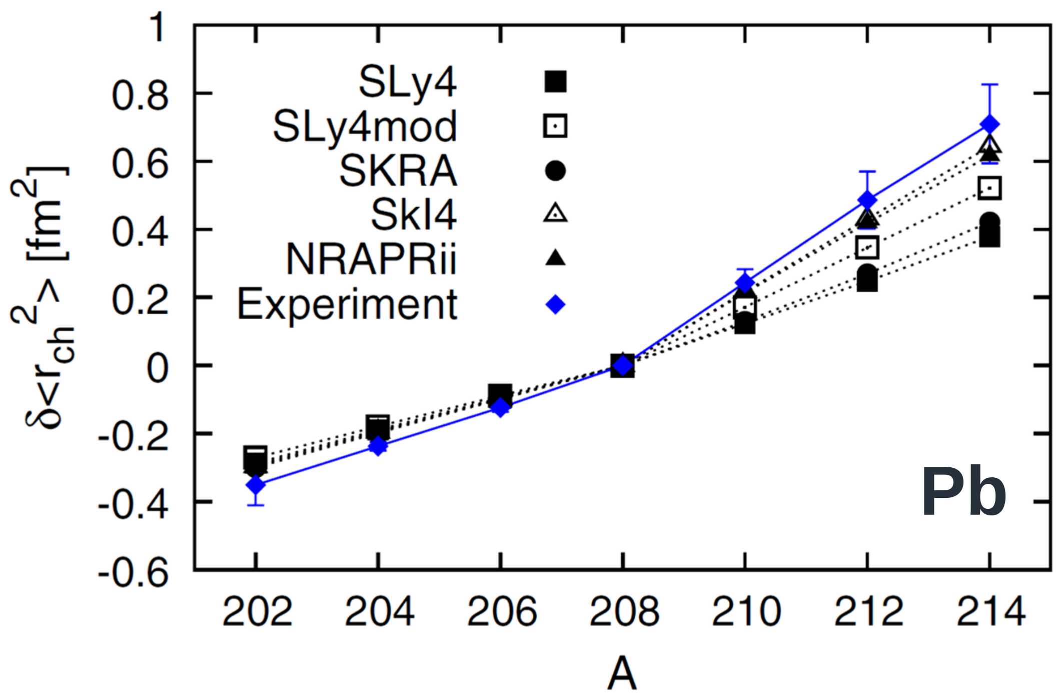
- Number of theoretical descriptions:
  P.M. Goddard *et al.*, PRL **110**, 032503 (2013)
  H. Nakada & T. Inakura, PRC **91**, 021302(R) (2015)
  H. Nakada, PRC **92**, 044307 (2015)

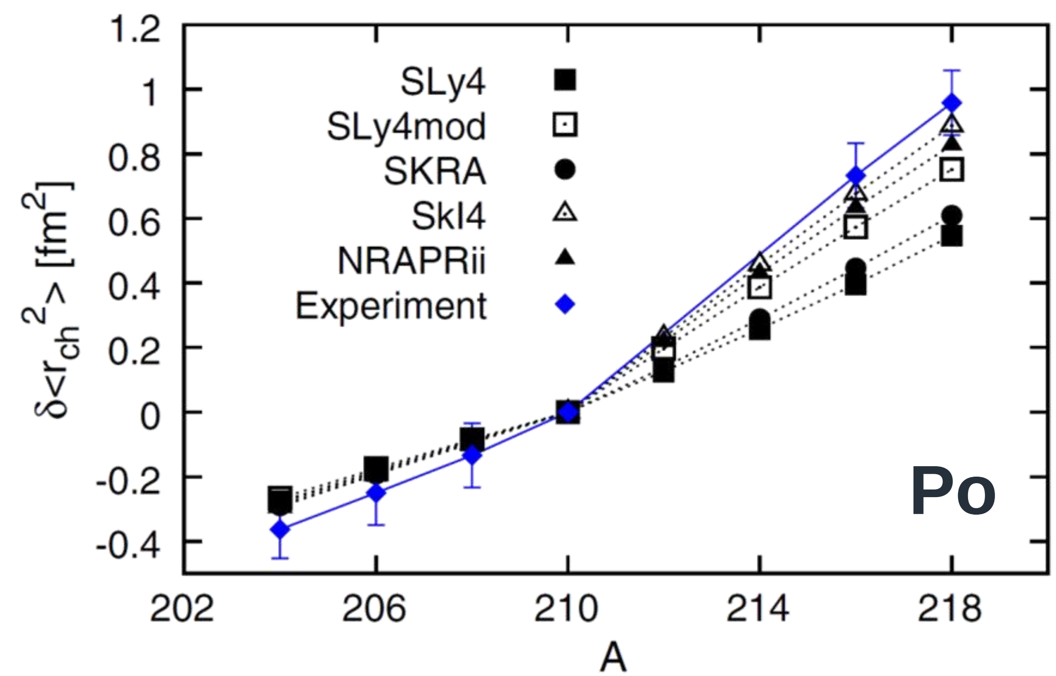
- Scattering of neutron pairs into large ℓ neutron orbitals - attractive proton-neutron interaction increases charge radius

- Near Z=82, N=126 neutron pairs scatter into $\nu i_{11/2}$



H. Nakada, PRC **92**, 044307 (2015)





Goddard, Stevenson and Rios, PRL **110**, 032503 (2013)

Comparison of theory & experiment

- However, effects of pairing should be significantly reduced when only one neutron outside of shell

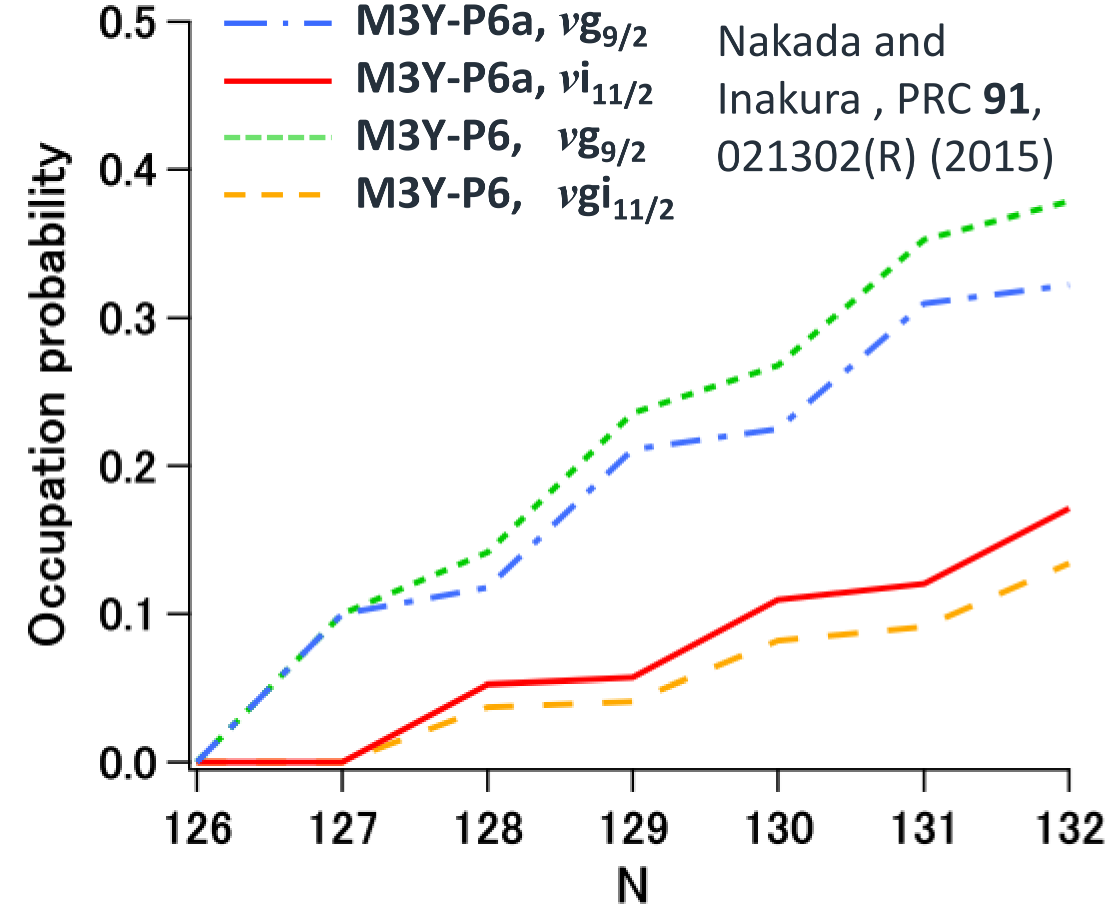
- In case of ^{214}Fr[a] and ^{210}Bi[b], mag. moms. suggested admixture between $[\pi h_{9/2}, \nu g_{9/2}]$ and $[\pi h_{9/2}, \nu i_{11/2}]$ configurations.

  [a] G. J. Farooq-Smith *et al.*, Phys. Rev. C **94**, 054305 (2016)

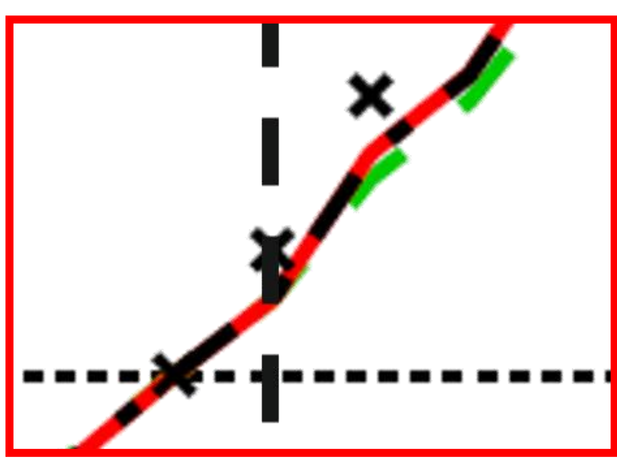
  [b] L. Szybisz, Nucl. Phys. A **244**, 107 (1975) & H. Behrens and L. Szybisz, Nucl. Phys. A **223**, 268 (1974)

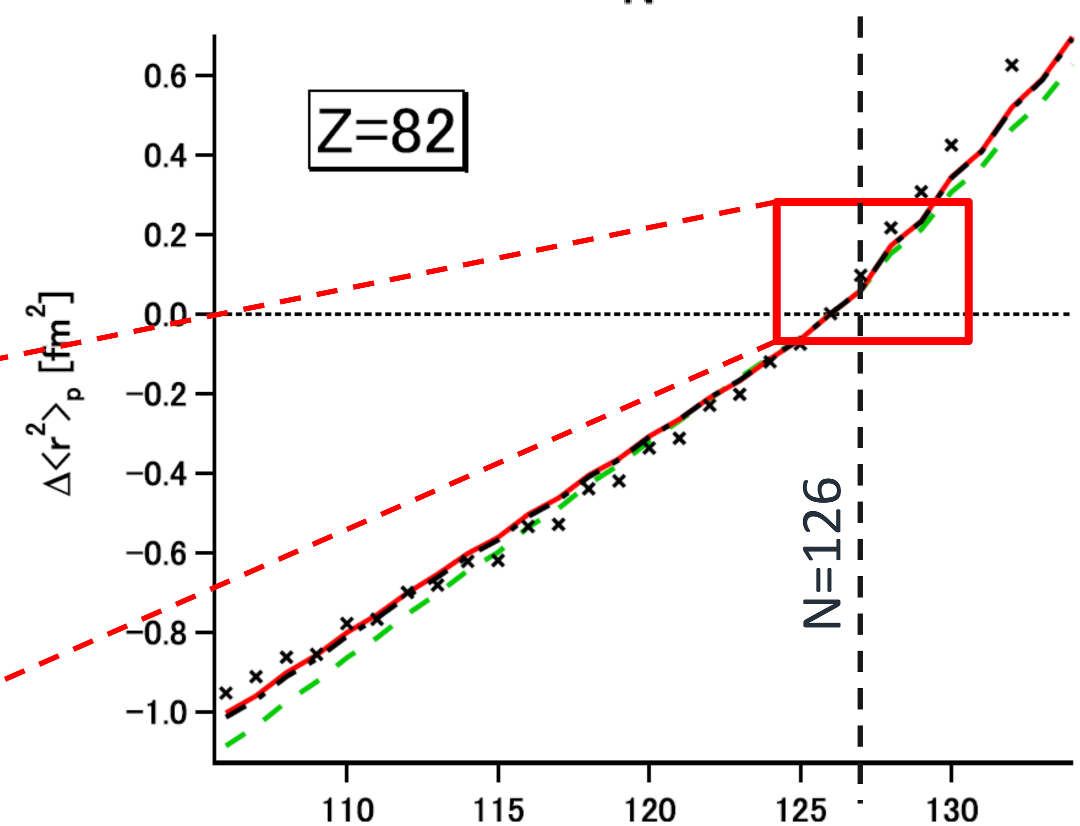
- However, ^{209}Pb and ^{211}Po which have mag. moms. consistent with pure $\nu g_{9/2}$ states

- Nakada show no occupation of $\nu i_{11/2}$ at N=127, and kink appears to only starts after N=127



Nakada and Inakura , PRC **91**, 021302(R) (2015)





H. Nakada, PRC **92**, 044307 (2015)

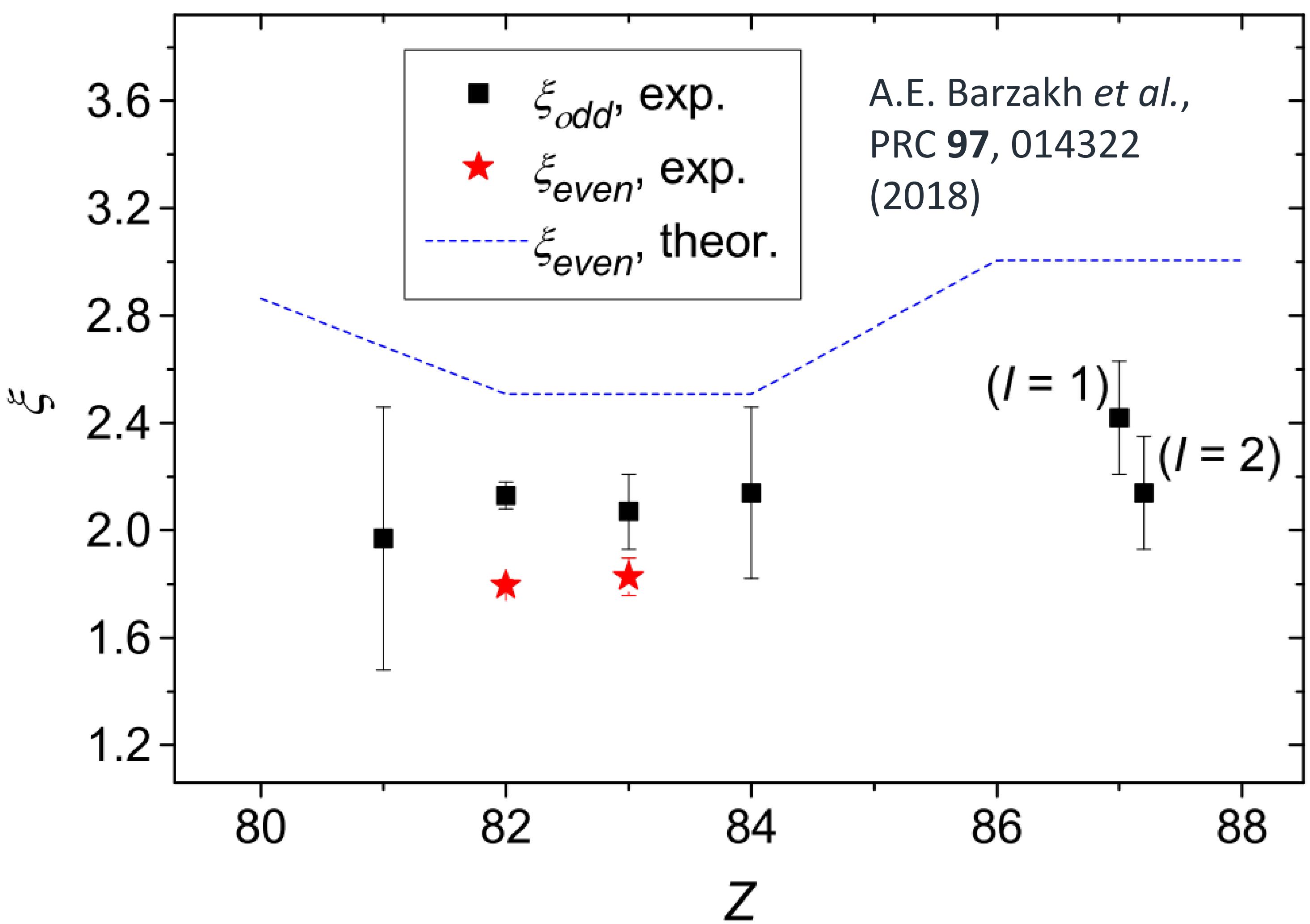
Kink at N=127

- We can compare gradients in radii just above and below shell closure – removes deformation effects of

$$\xi_{\text{even}} \equiv \frac{\delta\langle r^2\rangle_{128,126}}{\delta\langle r^2\rangle_{126,124}} = \frac{\delta\nu^{\text{FS}}_{128,126}}{\delta\nu^{\text{FS}}_{126,124}}$$

$$\xi_{\text{odd}} \equiv \frac{\delta\langle r^2\rangle_{127,126}}{\delta\langle r^2\rangle_{125,124}} = \frac{\delta\nu^{\text{FS}}_{127,126}}{\delta\nu^{\text{FS}}_{125,124}}$$

- This also minimizes the effects of odd-even staggering in radii (though may not be fully removed)



Kink at N=127

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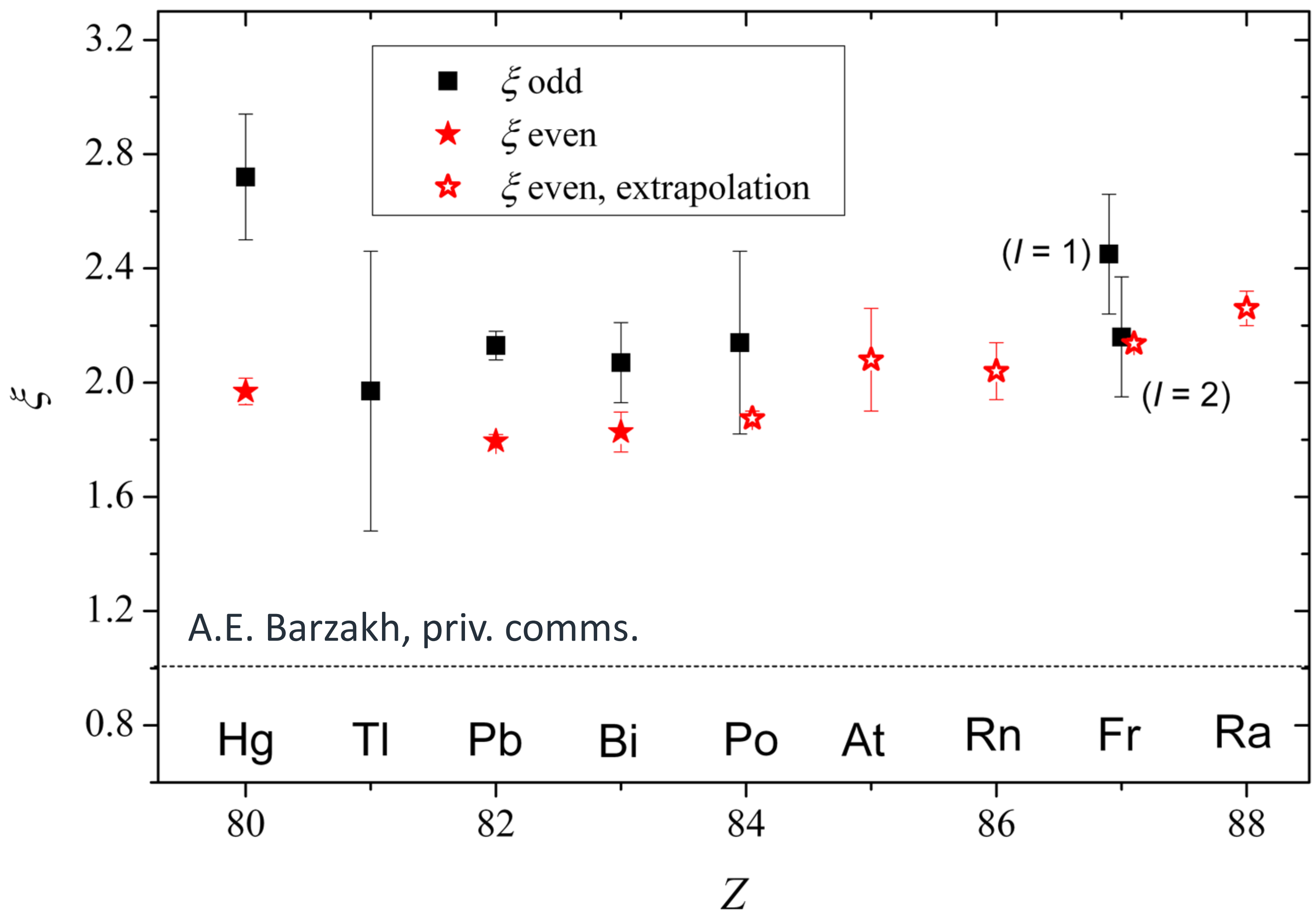
- This also minimizes the effects of odd-even staggering in radii (though may not be fully removed)

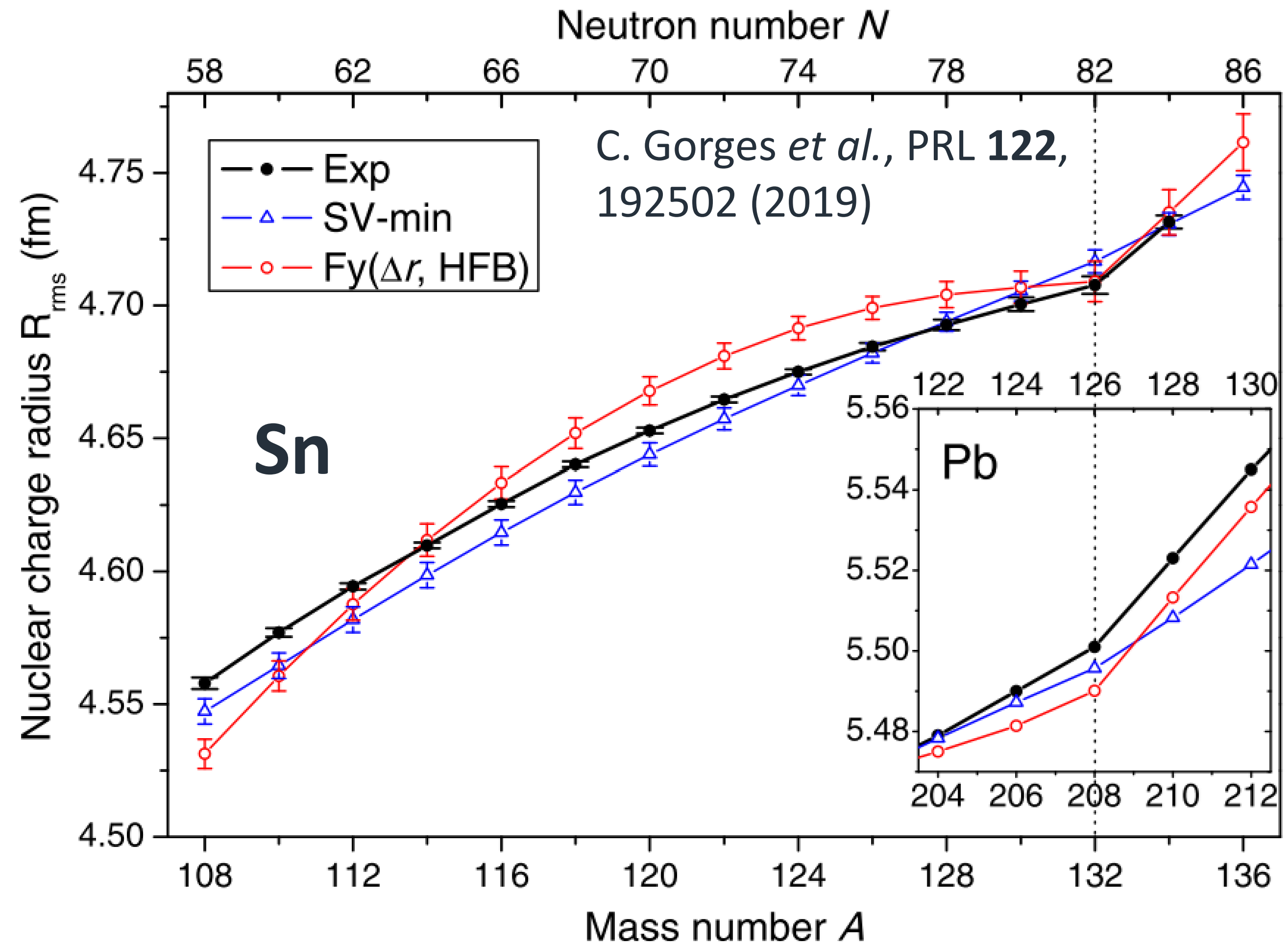
- We do observe a kink in odd-N at N=127

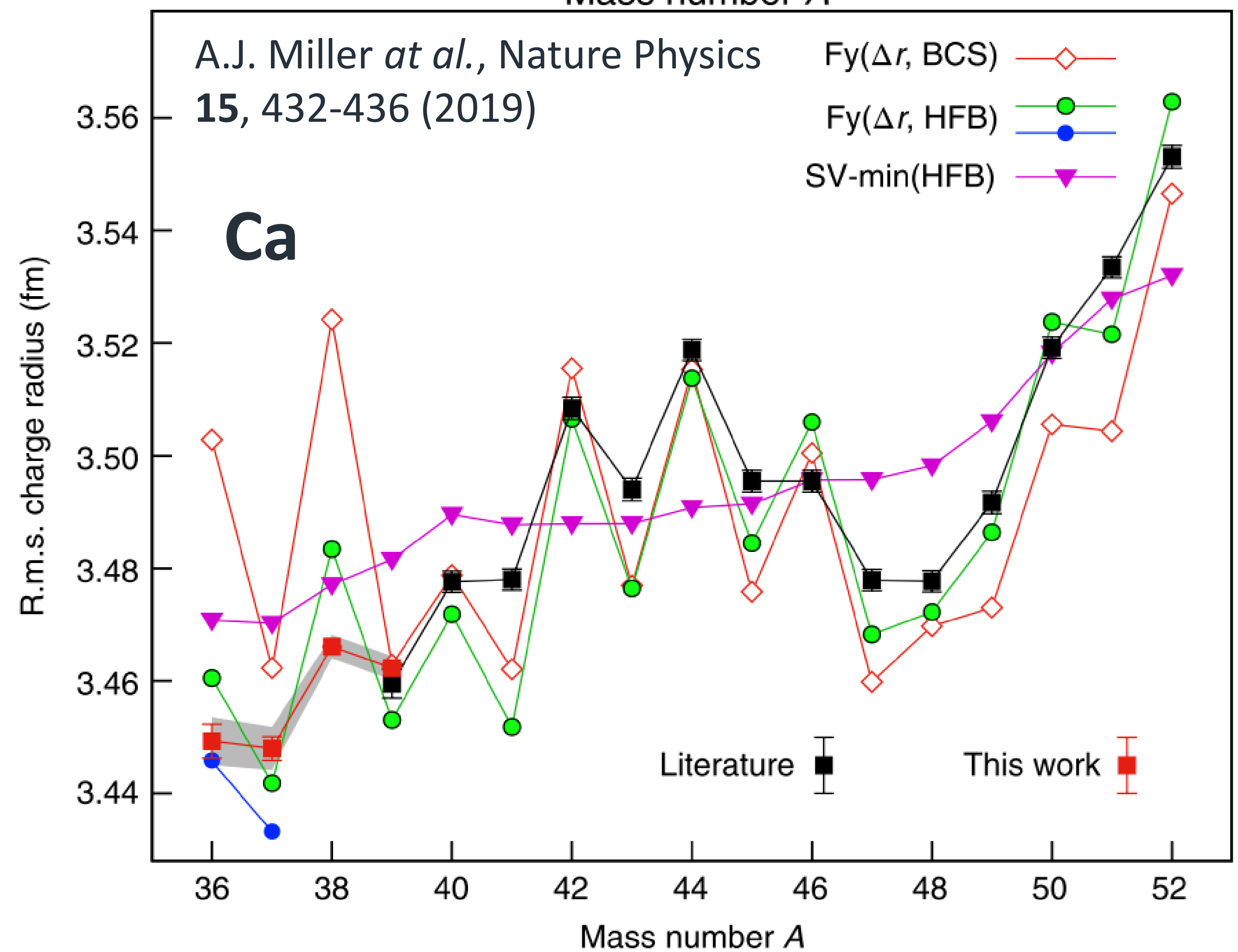
- Magnitude of kink is comparable in different chains and in both the odd- and even-N isotopes



Fayans functional

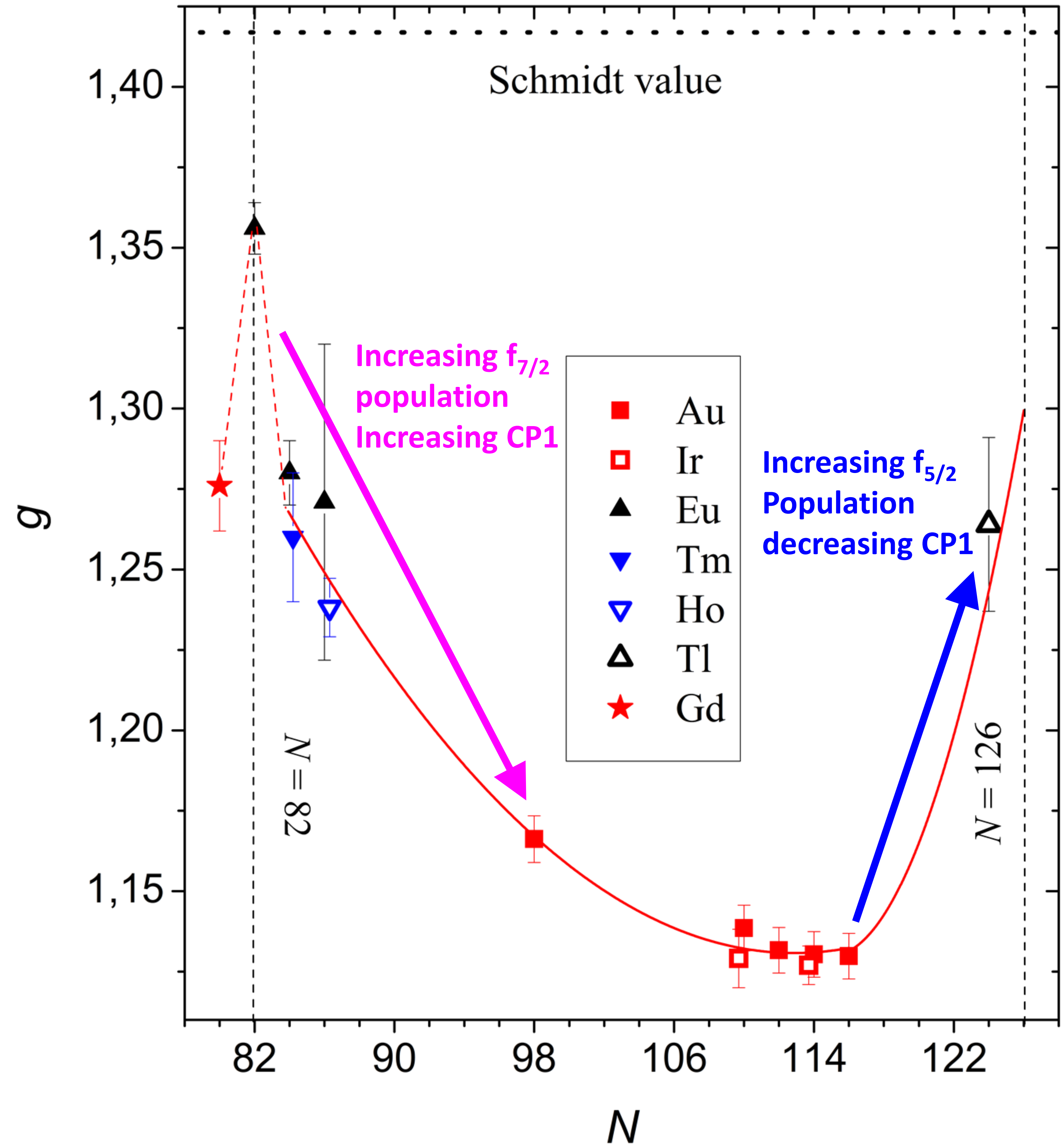
- Kink is a result of reduced neutron pairing for magic-N nuclei
- In comparison, neutron pairing is large for N±2 neighbours
- Fayans [Fy(Δr,HFB)] reproduces kinks at:
  N=48, Ca isotopes
  N=82, Sn isotopes
  N=126, Pb isotopes
- Some questions:
  - Odd-N calculations for Sn and Pb?
  - Are other observables reproduced? (i.e. mag. moms.)
  - Does the same gradient term in pairing explain kink for 1 neutron outside of a closed shell?





$g(\pi h_{11/2})$ systematics

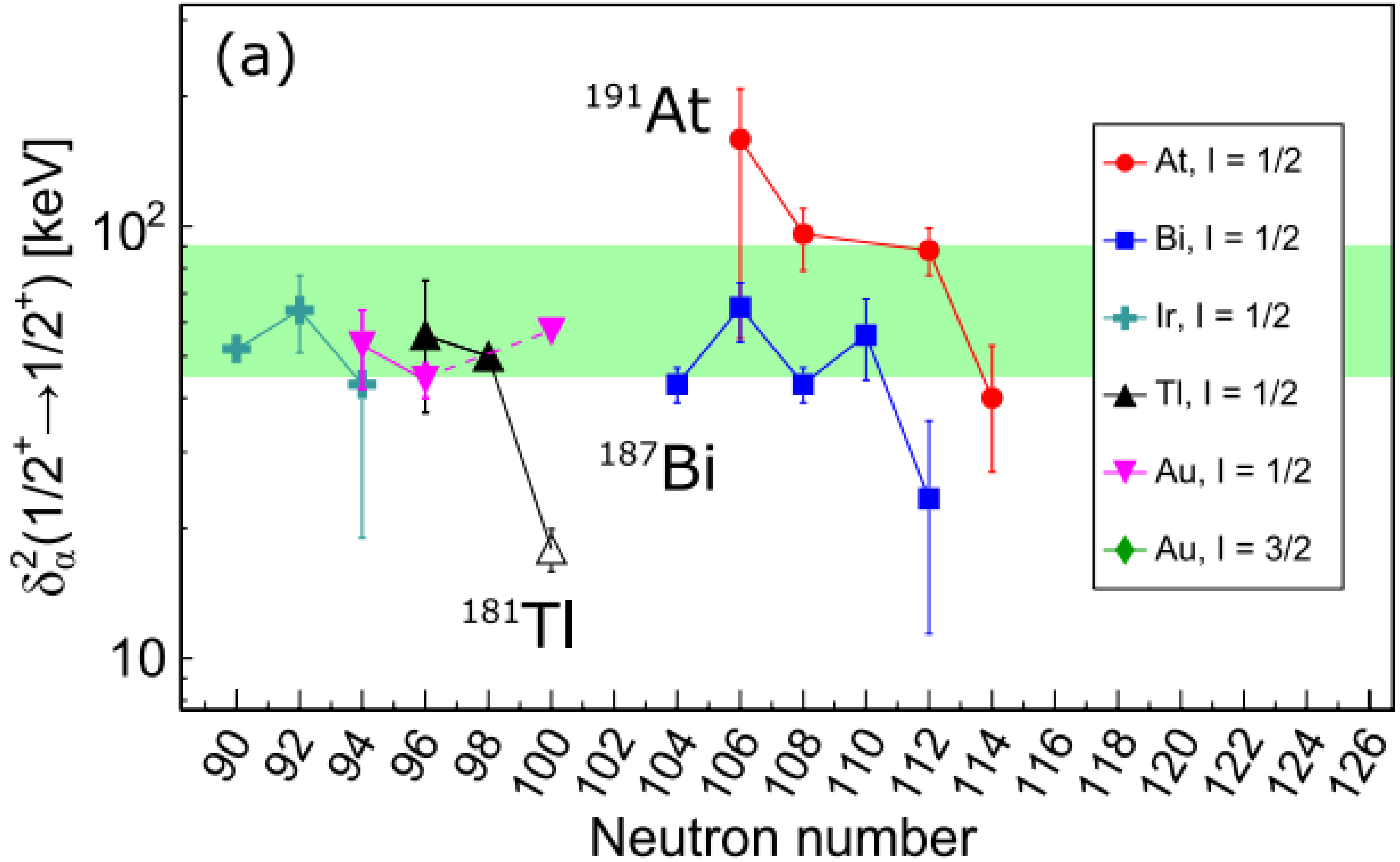
- $g(\pi h_{11/2})$ measured for isotopes from Z=64 to Z=81, observe effect of N=82 and N=126 shell effects on mag mom
- Possibly caused by first-order core polarization (CP1) effects, related to $f_{7/2} \rightarrow f_{5/2}$ neutron excitations
- CP1 correction for neutrons have opposite sign to $\pi h_{11/2}$, results in reduction of $g(\pi h_{11/2})$
- **Need more data at N≈126, gaps need filling to confirm systematic trend**

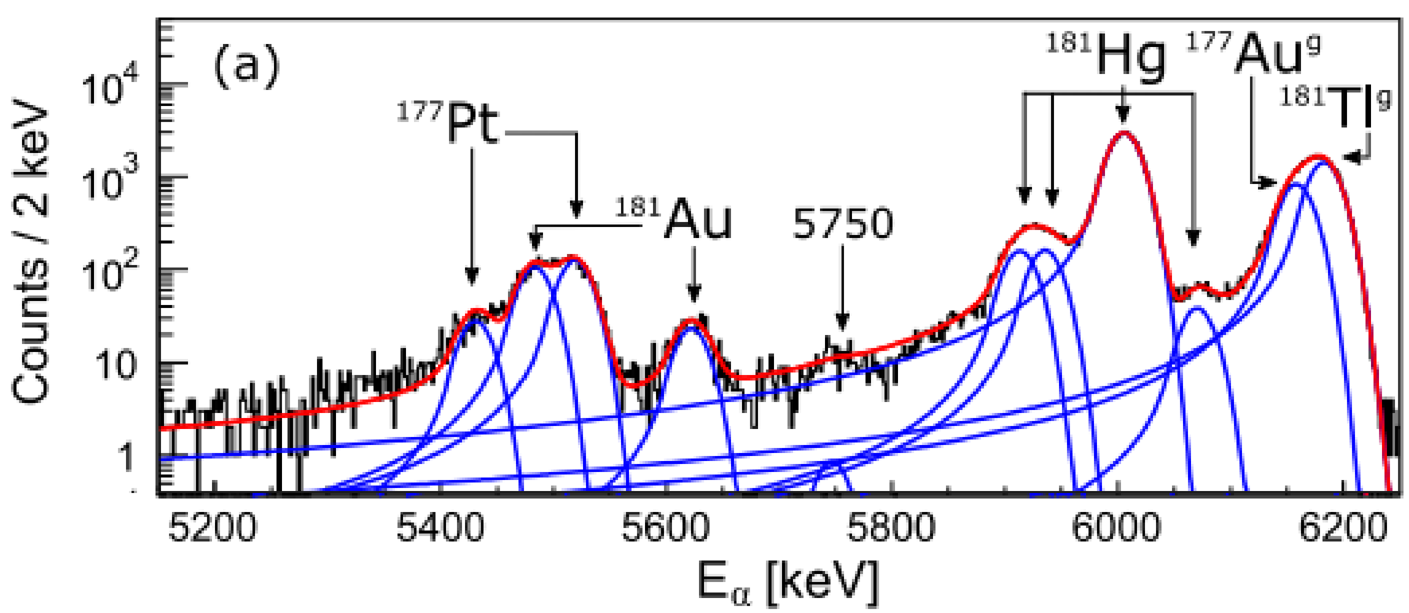


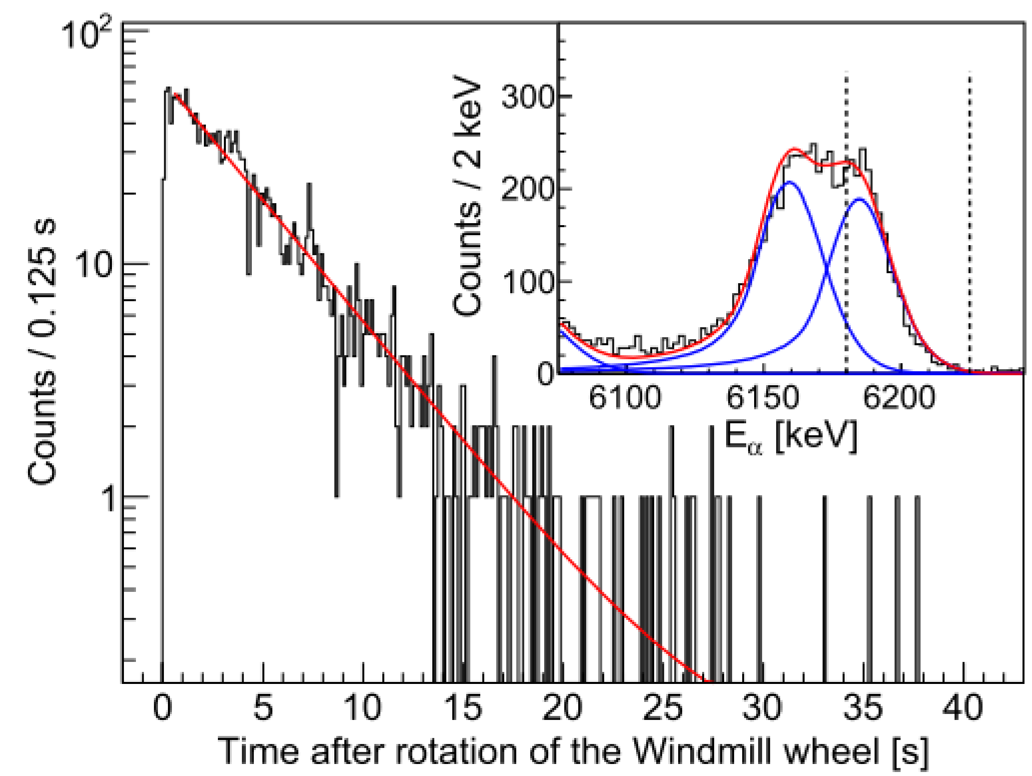
A.E. Barzakh *et al.*, PRC **101**, 034308 (2020)

Reduced widths and mag. moments

- First sign of evolving structures came from observation of small δ_α^2 for decay of ^{181}Tl



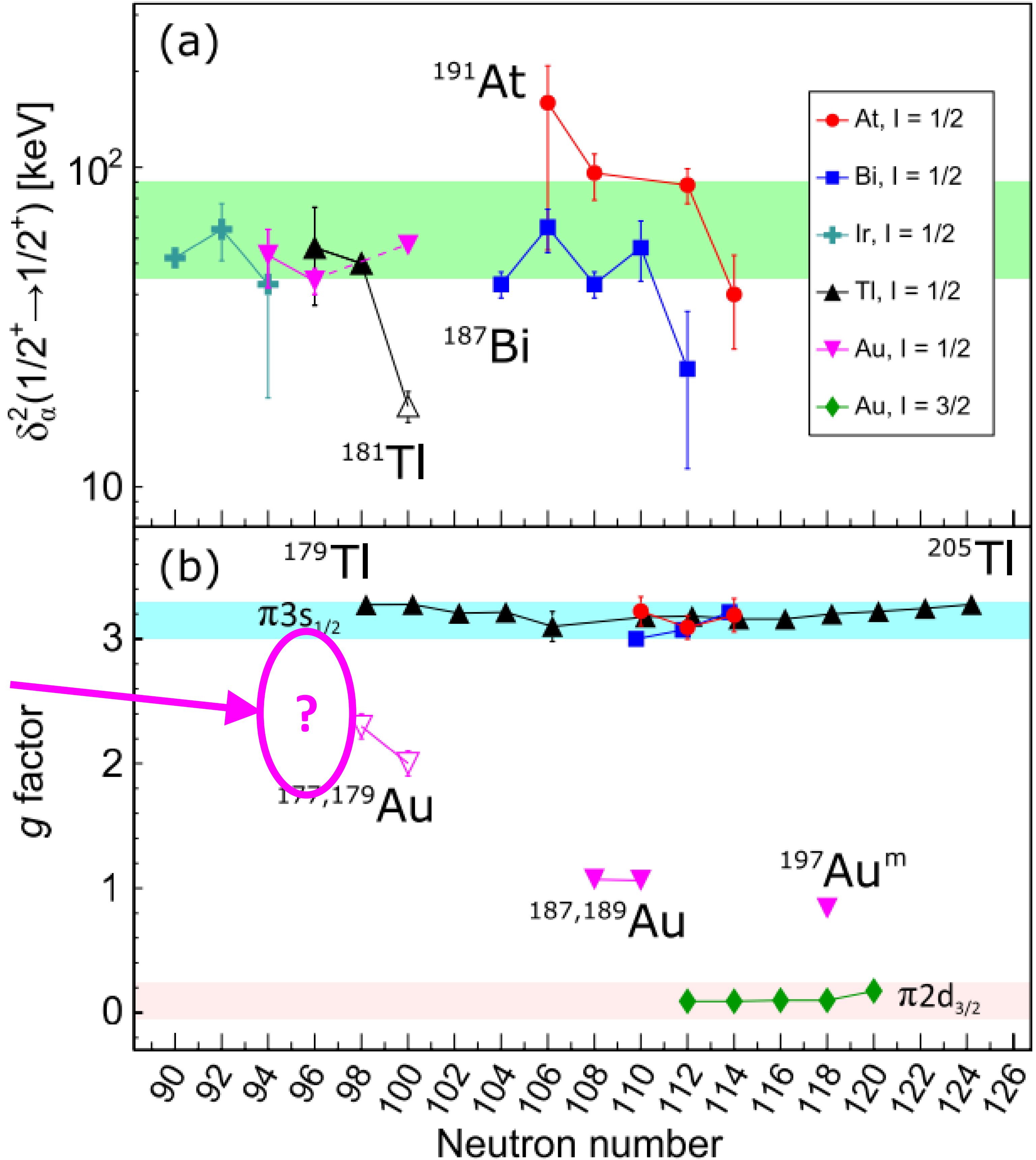




J.G. Cubiss *et al.*, PLB **786**, 355-363 (2018)

Reduced widths and mag. moments

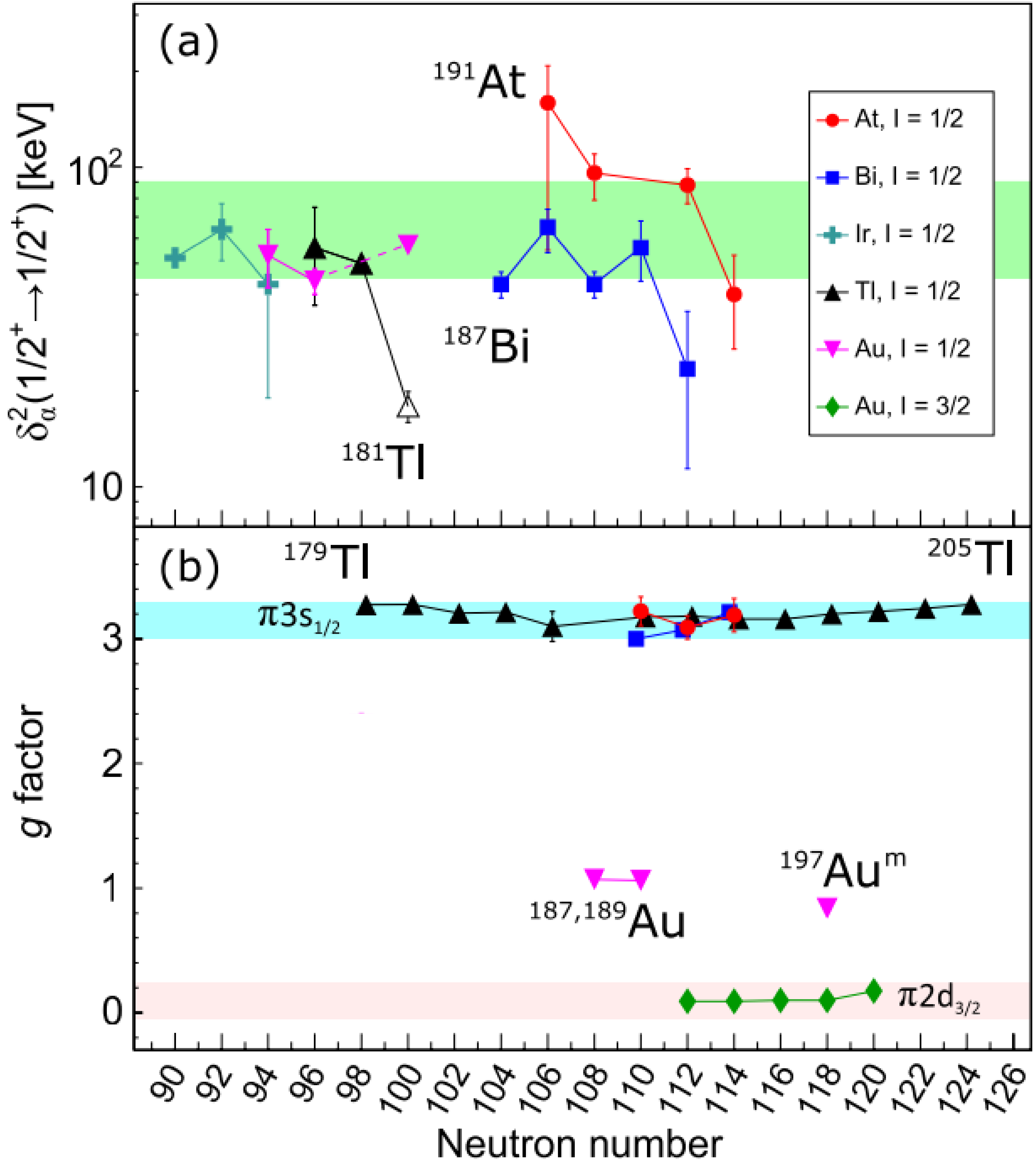
- ^{177,179}Au g factors lie between $\pi s_{1/2}$ states of Tl, Bi and At nuclei and the $\pi d_{3/2}$ states in other Au
- **Suggests that these are mixed $\pi s_{1/2}$/ $\pi d_{3/2}$ configurations** with the degree of mixing changing as neutron number reduces
- Important to see whether apparent trend continues for I=1/2 state in ^{175}Au ($T_{1/2}$=207 ms)
- Alpha decay of ^{183}Tl is unhindered suggests pure $\pi s_{1/2}$ state in ^{175}Au
- Would mean a rearrangement of $\pi s_{1/2}$ and $\pi d_{3/2}$ states in lightest Au



J.G. Cubiss *et al.*, PLB **786**, 355-363 (2018)

Reduced widths and mag. moments

- First sign of evolving structures came from observation of small δ_α^2 for decay of ^{181}Tl
- Dipole moment of ^{181}Tl indicates pure $\pi s_{1/2}$ configuration, as expected in this region
- Interesting to note that g factor not affected by deformation:
  - $\pi s_{1/2}$ in Tl are spherical
  - $\pi s_{1/2}$ in At & Bi are deformed
- **Is the hindrance related to structure of daughter, ^{177}Au?**

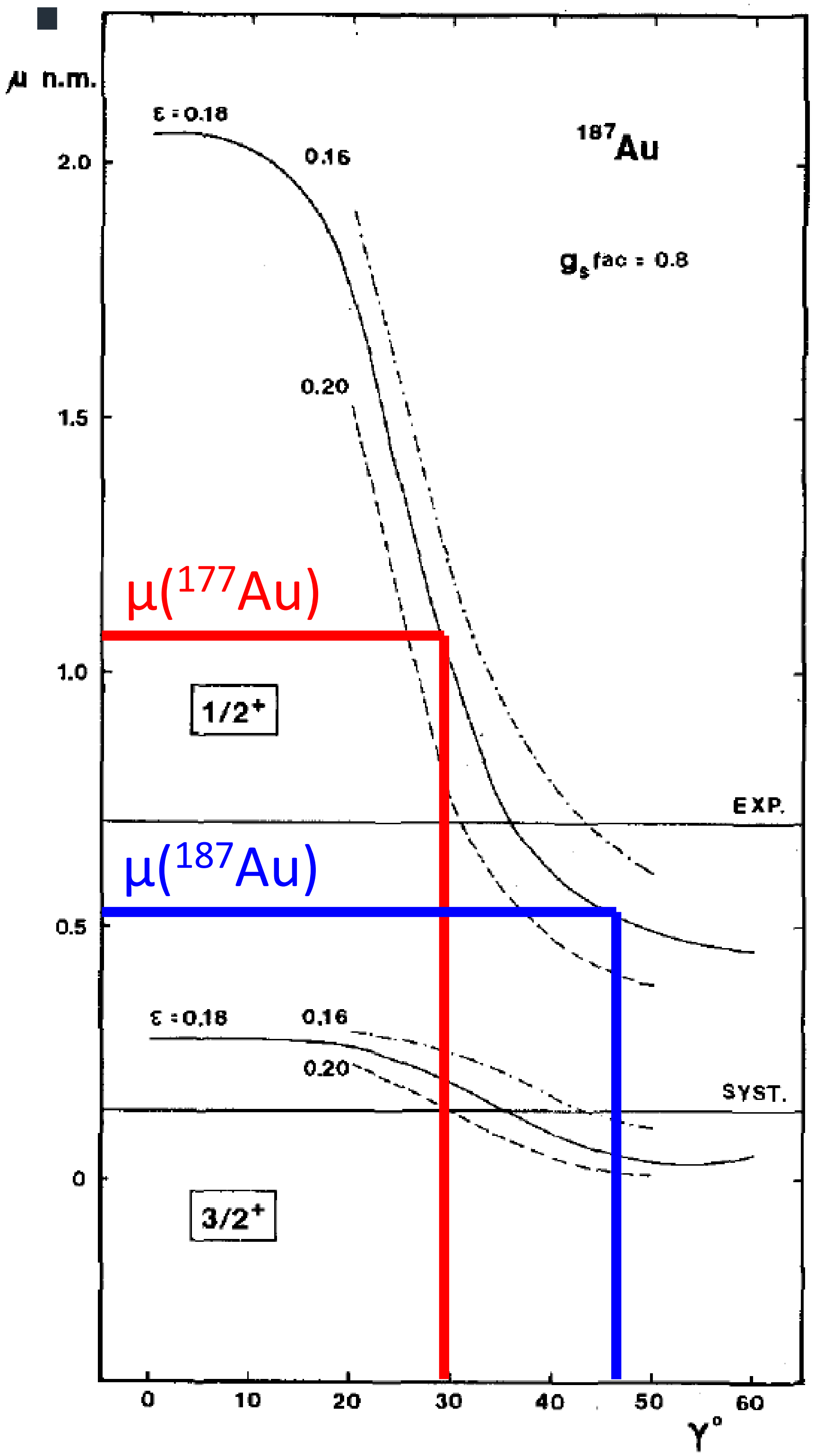


J.G. Cubiss *et al.*, PLB **786**, 355-363 (2018)

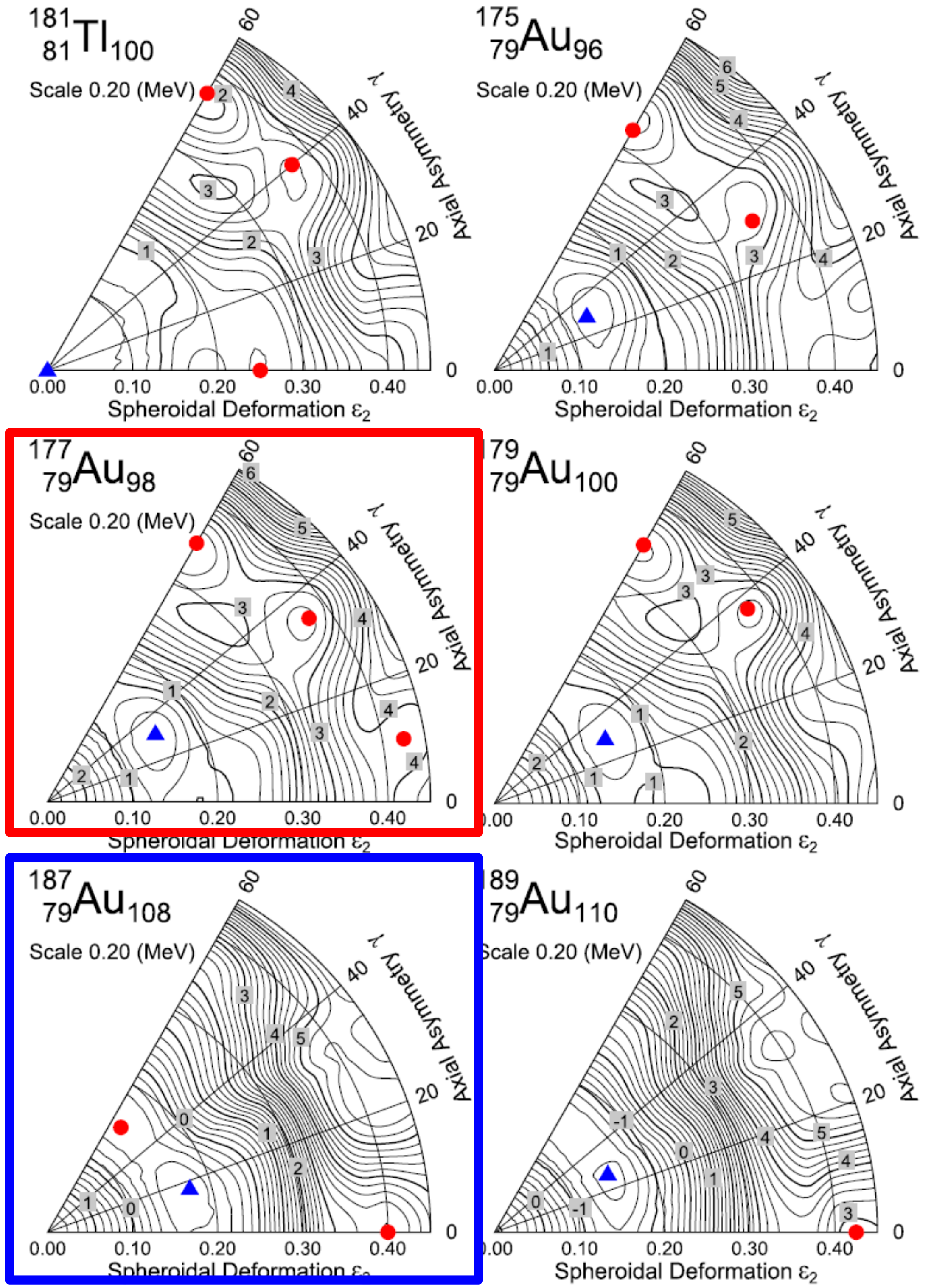
Dipole moment evidence for triaxiality?

- PTRM calculations showed strong dependence of I=1/2 state mag moms on degree of triaxiality

- **Further theoretical investigation required**



C. Ekstrom *et al.*, Nuc. Phys. A**348**, (1980) 25-44



P. Moller *et al.*, At. Data Nucl. Data Tables **98** (2), (2012) 149-300

In 2017-run we succeeded in measurement of $Q_s(^{188}Bi^{ls})$.
Deformation parameter β_Q extracted from Q_s coincides with β from $\delta<r^2>$ and unambiguously testifies to the strong prolate deformation of $^{188}Bi^{ls}$

$$\delta < r^2 > = \delta < r^2 >_{DM} + \frac{5}{4\pi} < r^2 >_{DM} \delta < \beta_{DM}^2 >$$

$$\beta_{DM} \equiv < \beta_{DM}^2 >^{1/2}$$

$$Q_s = \frac{I \cdot (2I-1)}{(I+1)\cdot(2I+3)} \cdot \frac{3}{\sqrt{5\pi}} \cdot Z \cdot R_0^2 \cdot \beta_Q \cdot (1 + \frac{1}{7} \cdot \sqrt{\frac{20}{\pi}} \cdot \beta_Q + \ldots)$$