Laser spectroscopy as a probe for the size and shape of exotic nuclei

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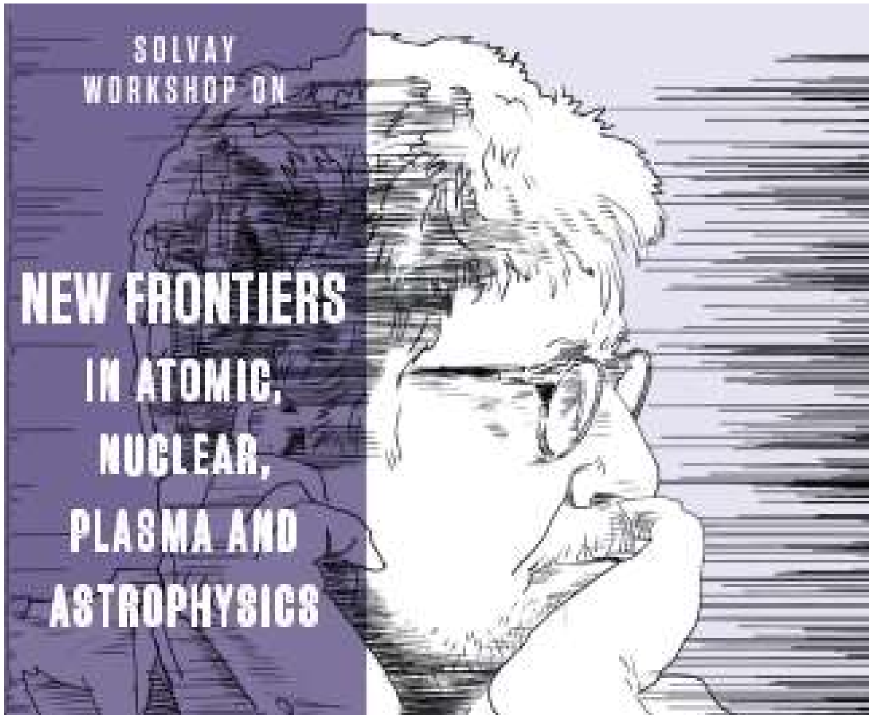

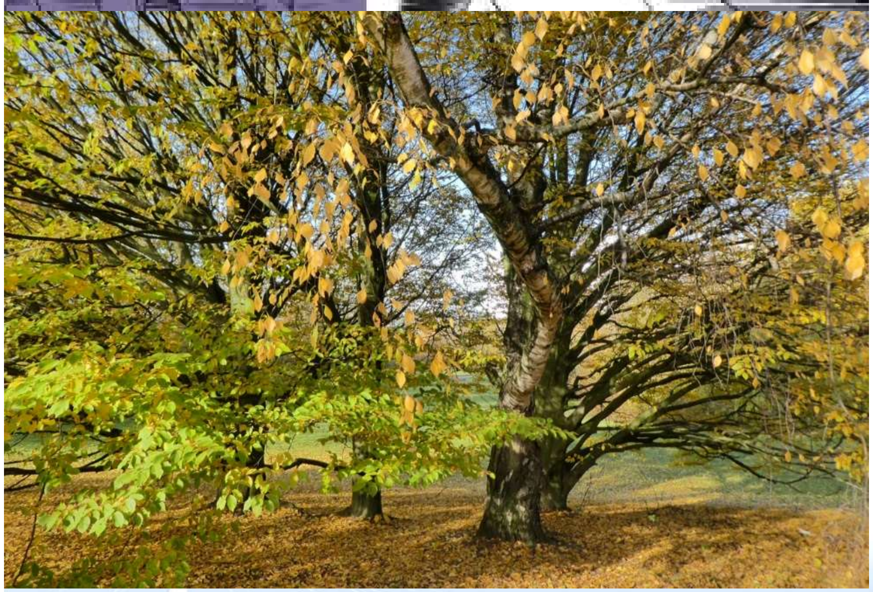

Outline

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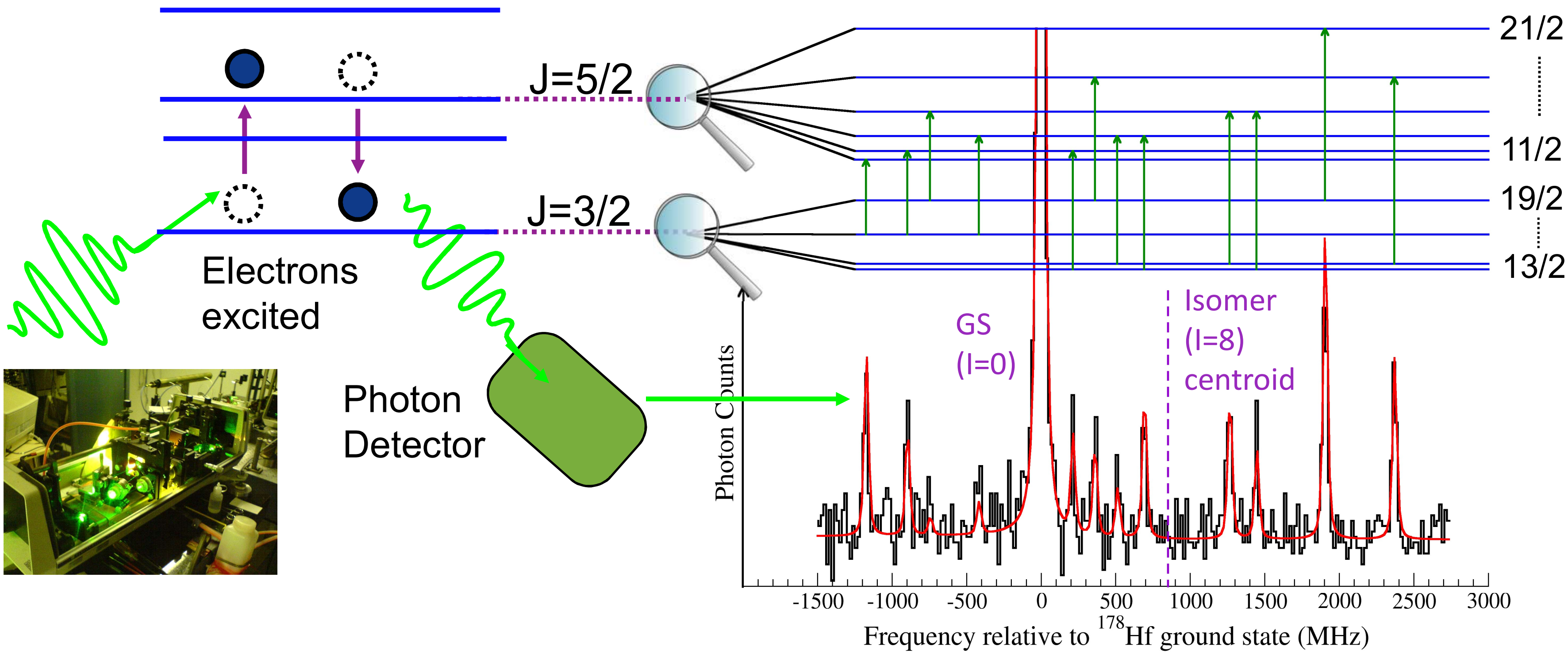
- Laser spectroscopy for atomic nuclei and traditional methods
- Nuclear spin & electromagnetic moments

  - the story of copper (linked to Michel!)
- Shapes and shape coexistence in nuclei

  - from yttrium, to mercury and the lead region
- Summary

The nuclear fingerprint on atomic spectra

Fine structure — Electronic *hyperfine* structure



Observables: isotope shifts, hyperfine structure

$A = \dfrac{\mu_I B_e(0)}{I J}$	$B = eQ_s \left\langle \dfrac{\partial^2 V_e}{\partial z^2} \right\rangle$	I	$\delta\langle r^2\rangle$
Magnetic dipole interaction	Electric quadrupole interaction	Nuclear spin	Mean-square charge radii

Isotopic shifts of electronic transitions

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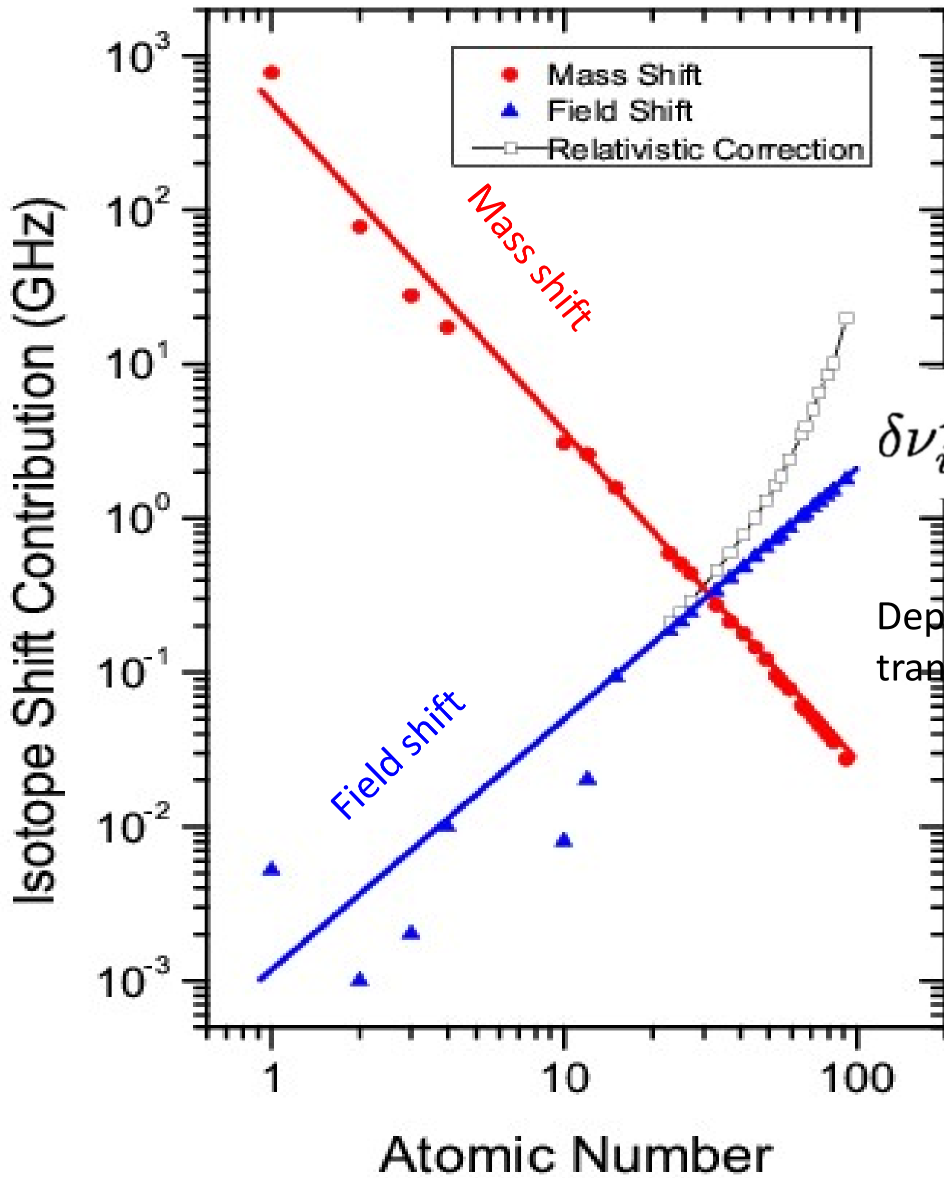
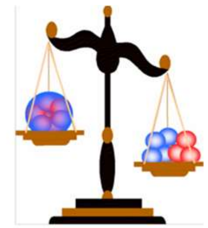
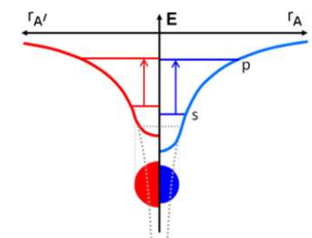


Nuclear mass



Nuclear volume



$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \boxed{\delta\langle r^2\rangle^{A,A'}}$$

Depends on optical transition, i, only

Depends on isotopes only

ation of IS data:

lass data from Atomic Mass Evaluation (2016)

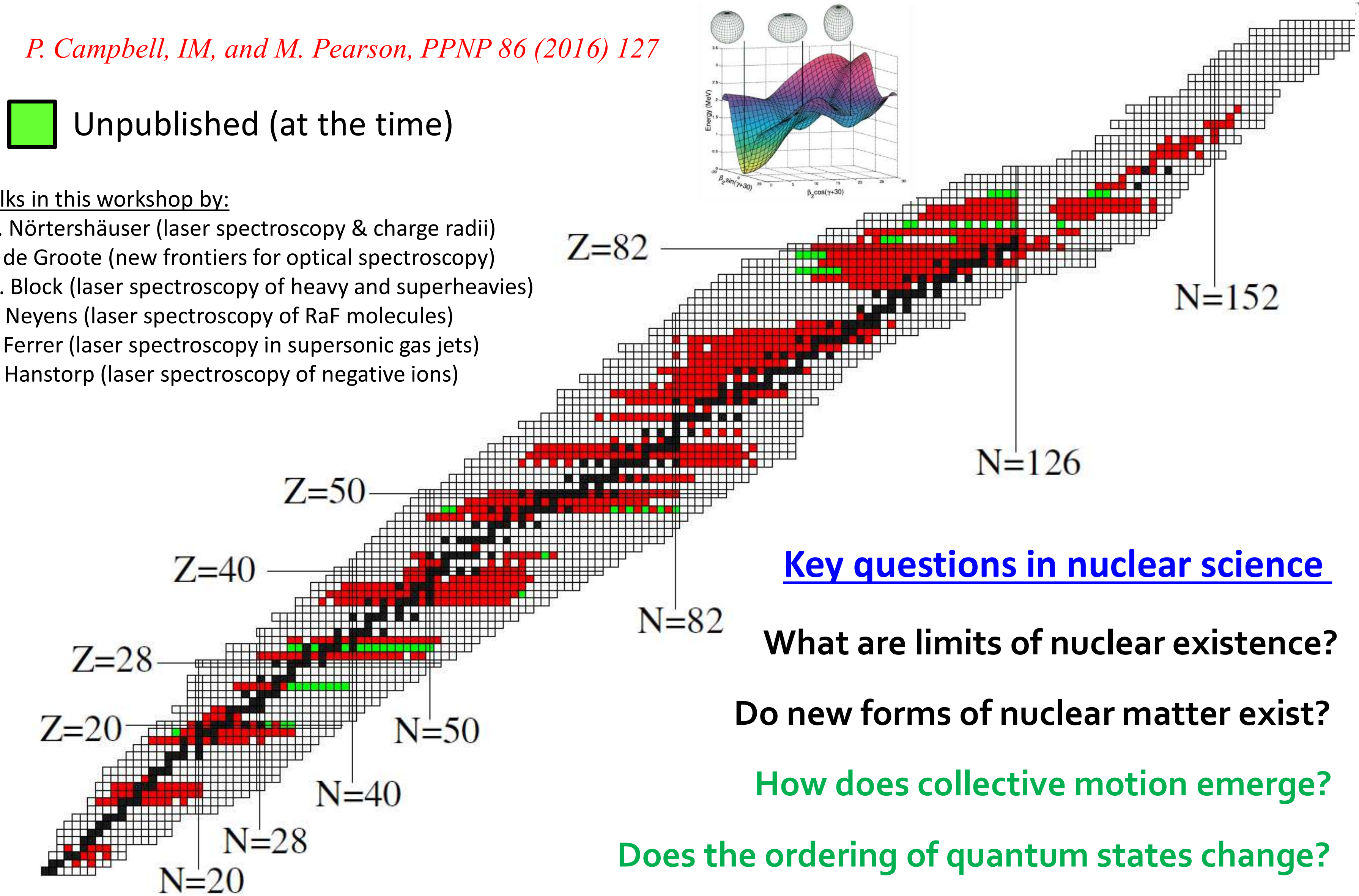
pecific mass shift (SMS) either calculated (*ab initio*, IBPT, coupled cluster) or evaluated via non-optical ata (elastic e- scattering, muonic atom X-rays…)

eld shift factor from non-optical, mi-empirical, atomic theory (~15%)

work by M. Godefroid

A laser spectroscopists' nuclear landscape

P. Campbell, IM, and M. Pearson, PPNP 86 (2016) 127



Talks in this workshop by:
W. Nörtershäuser (laser spectroscopy & charge radii)
R. de Groote (new frontiers for optical spectroscopy)
M. Block (laser spectroscopy of heavy and superheavies)
G. Neyens (laser spectroscopy of RaF molecules)
R. Ferrer (laser spectroscopy in supersonic gas jets)
D. Hanstorp (laser spectroscopy of negative ions)

Key questions in nuclear science

What are limits of nuclear existence?

Do new forms of nuclear matter exist?

How does collective motion emerge?

Does the ordering of quantum states change?

The Isotope Separation On-Line method

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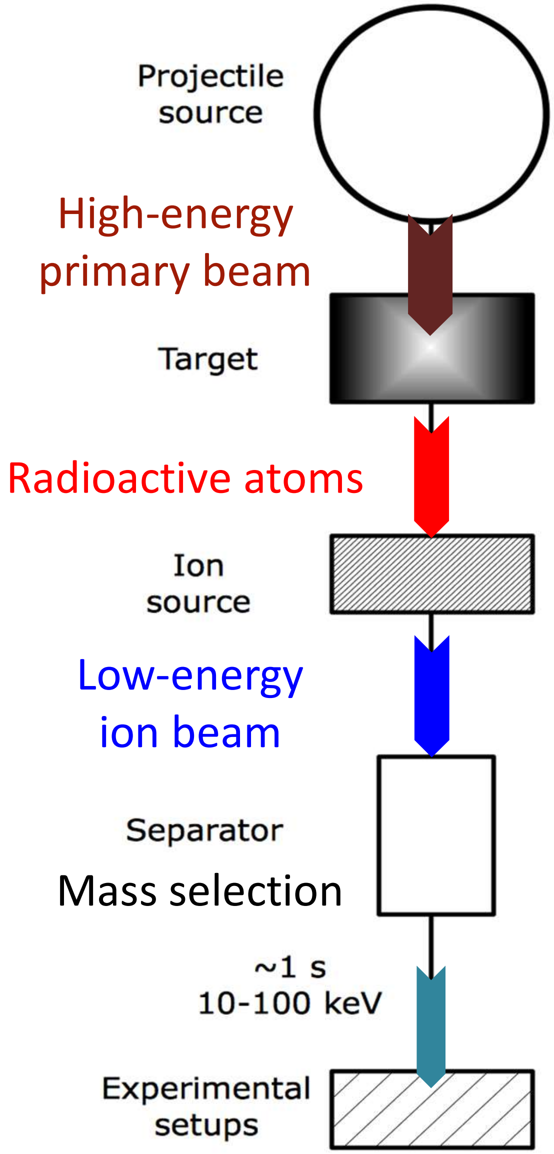
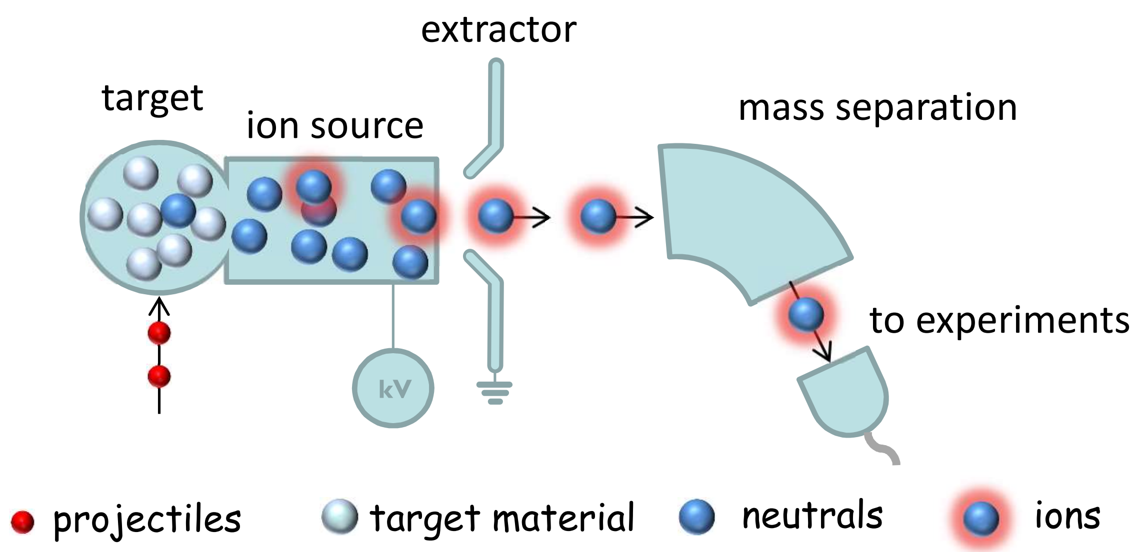
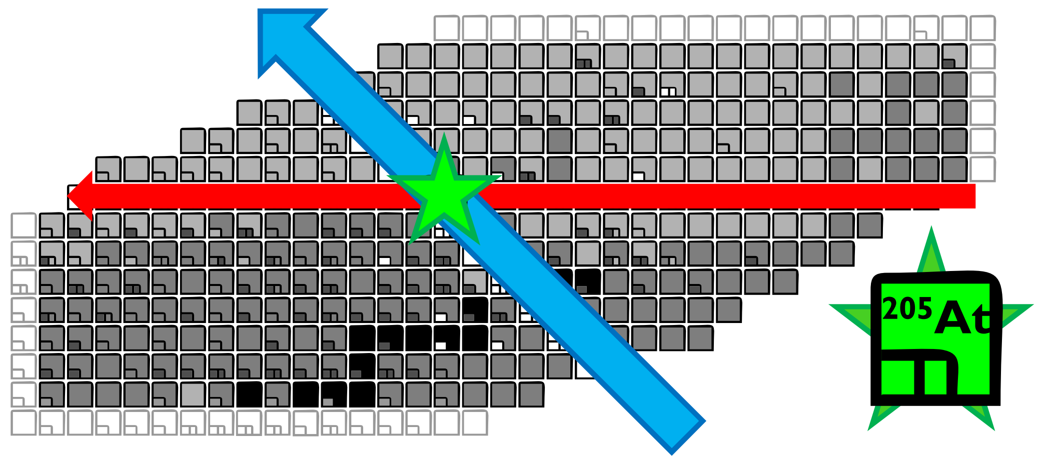
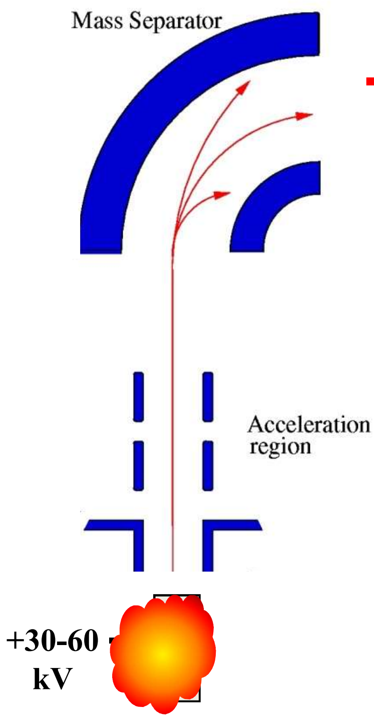


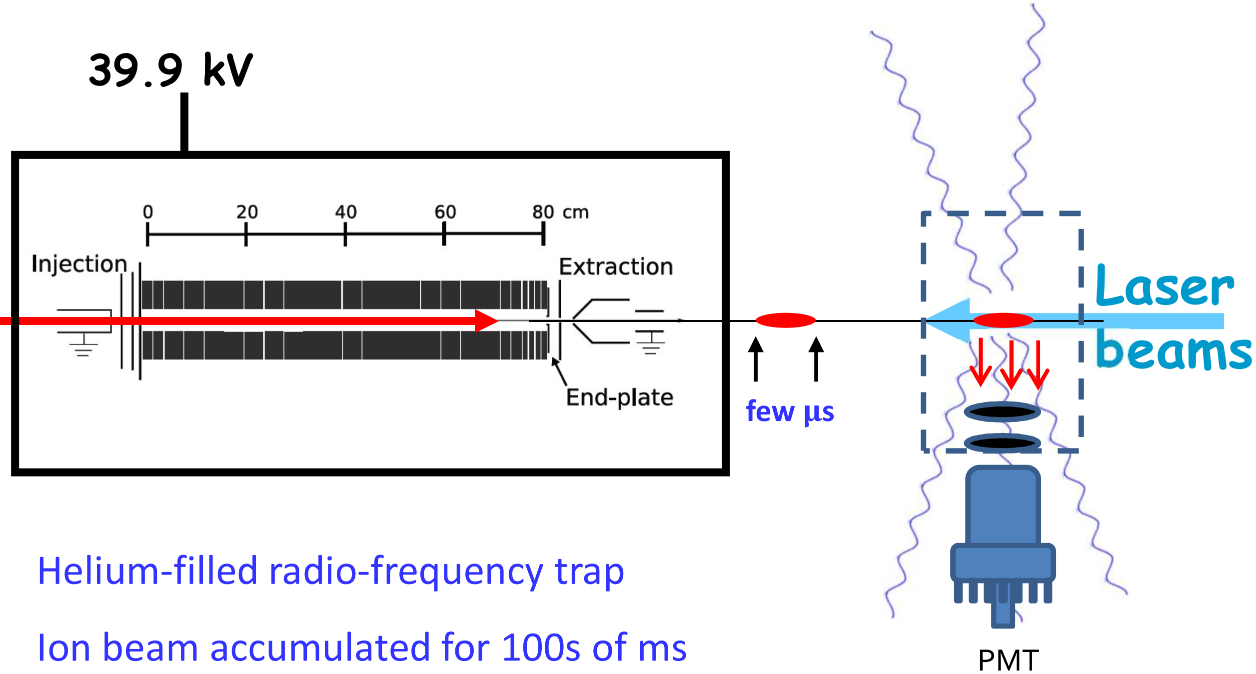




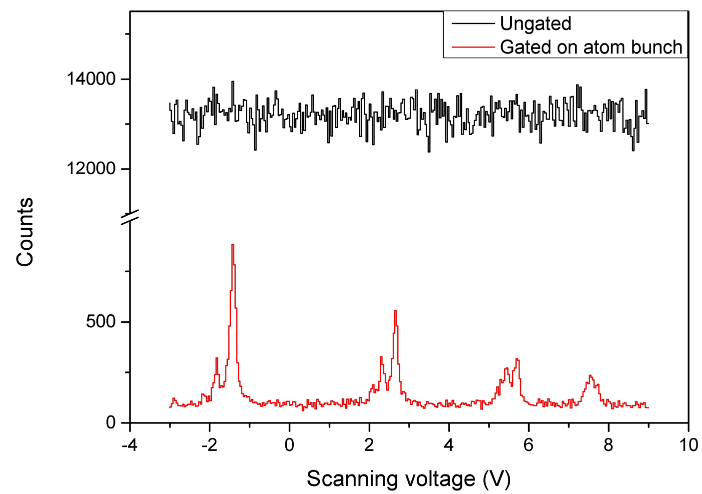
+ ^{205}Pb, Bi, Po, Rn, Fr…

High resolution collinear laser spectroscopy





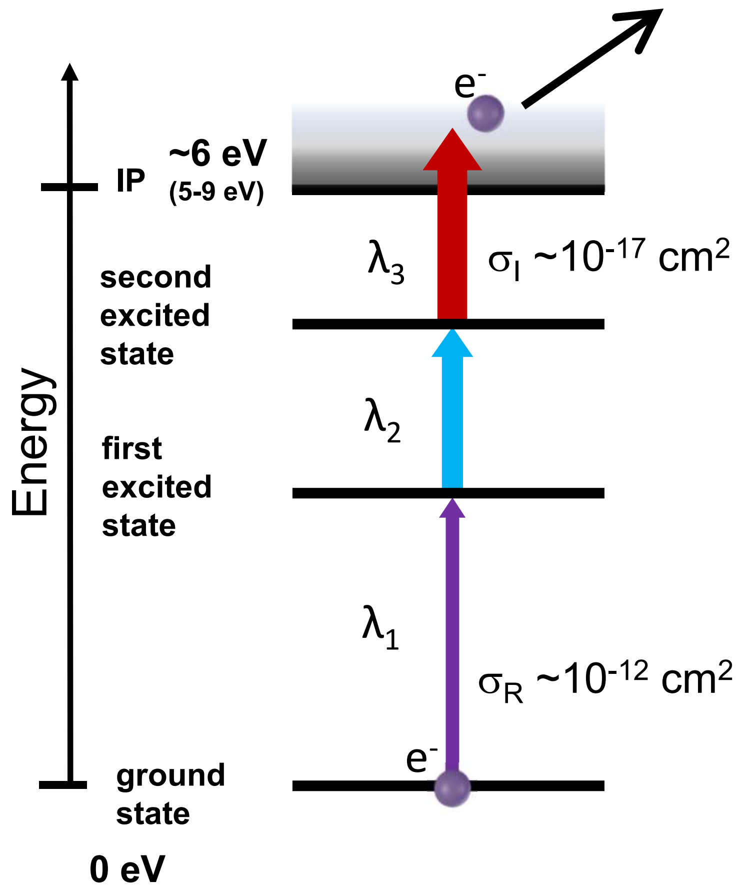
- Helium-filled radio-frequency trap
- Ion beam accumulated for 100s of ms
- Released as a few µs bunch
- Background suppression $\sim 10^4$
- Beam rates of 1000 s^{-1} required

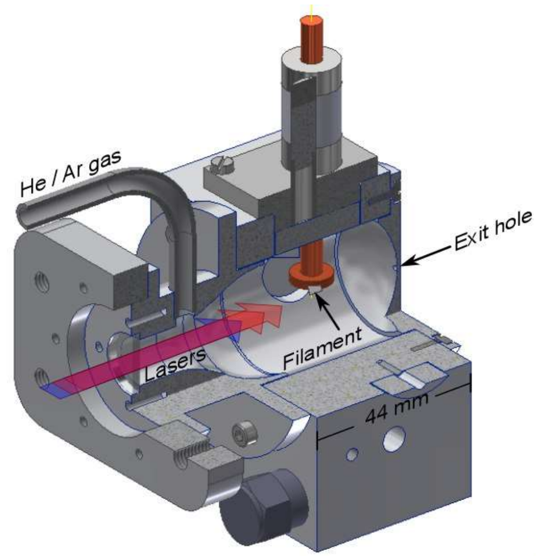


<u>Variants:</u>
Precision collinear laser spec (W. Nörtershäuser)
Collinear resonance ionization spectroscopy (G. Neyens)

In-source resonance ionization spectroscopy

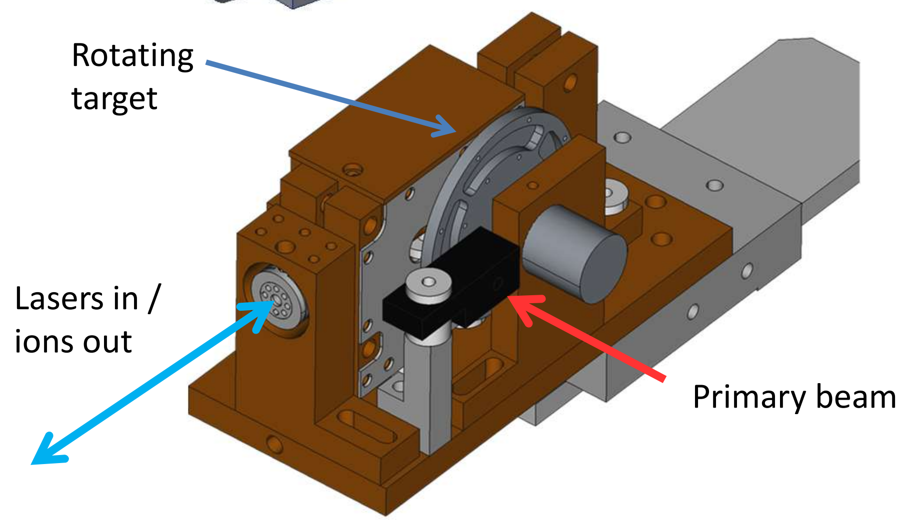
An efficient and selective method (combined with mass separation). Lower resolution than collinear laser spectroscopy.





In-gas cell laser resonance ionization
(eg IGISOL, Leuven, KISS, S^3, MARA-LEB, GSI)

Hot cavity approaches
(ISOLDE, GANIL, TRIUMF…)



Variants:
Gas cell coupled to separator (M. Block), gas jet (R. Ferrer)

Migration of quantum states

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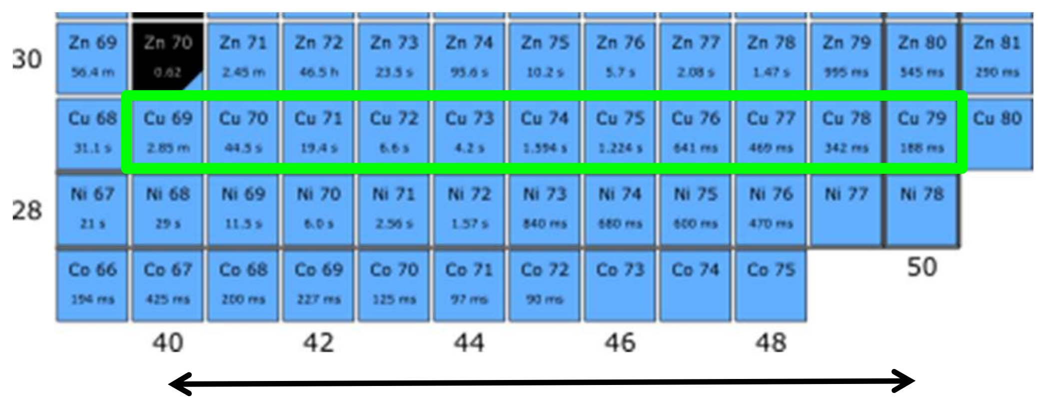
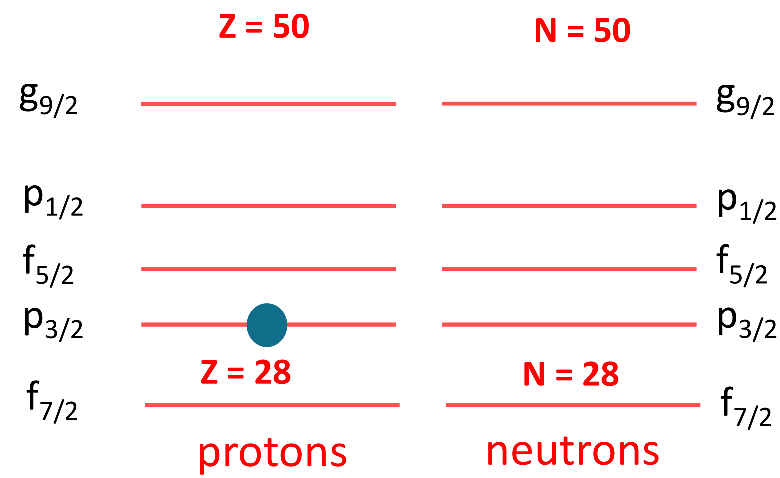
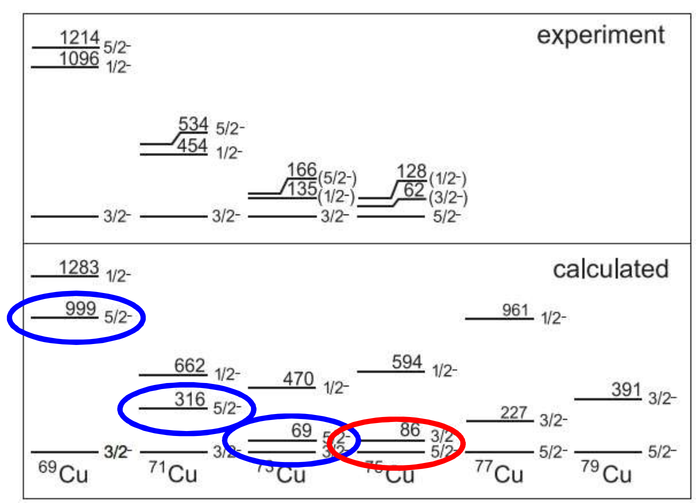
Example: neutron-rich copper (Z=29) isotopes



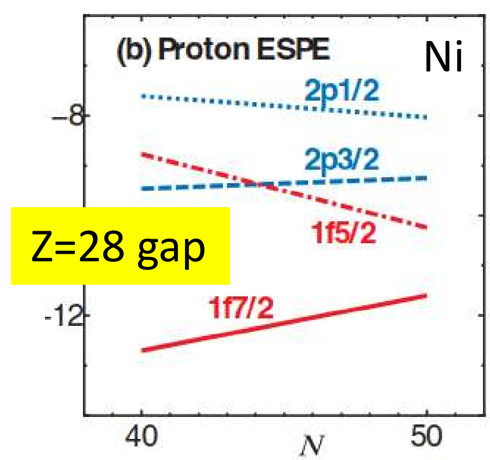
Neutrons filling $1g_{9/2}$ orbital





K.T. Flanagan et al., Phys. Rev. Lett. 103 (2009) 142501

T. Otsuka et al., Phys. Rev. Lett. 95 (2005) 232502



- Energy of proton & neutron quantum orbits depends on the number of protons/neutrons in the nucleus
- Magic numbers change!
- Predicted inversion of the proton $p_{3/2}$ state and $f_{5/2}$ state at N=45

From in-source to collinear laser spectroscopy

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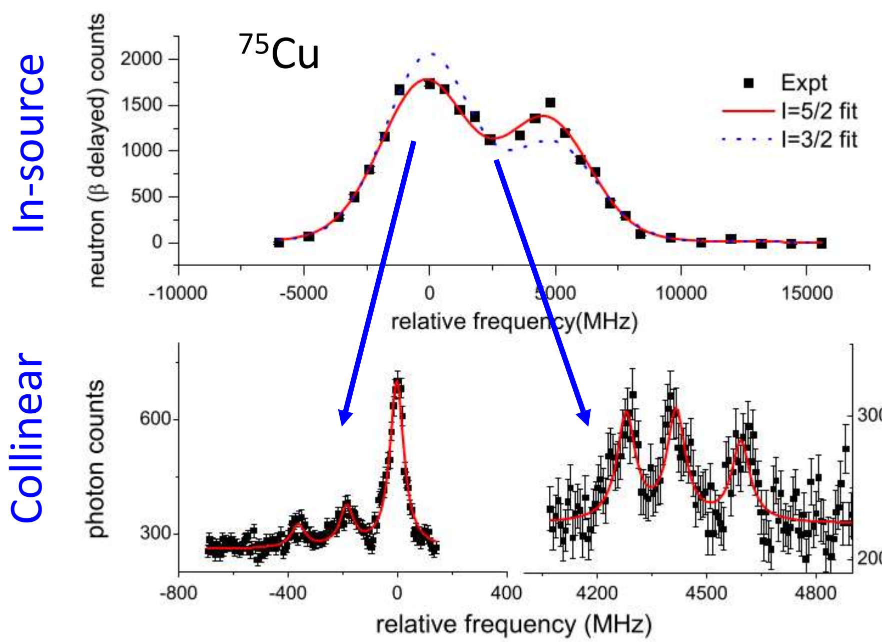
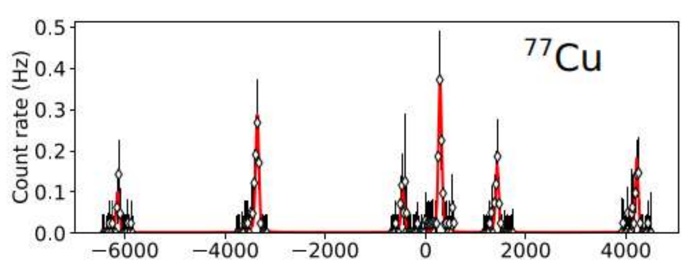


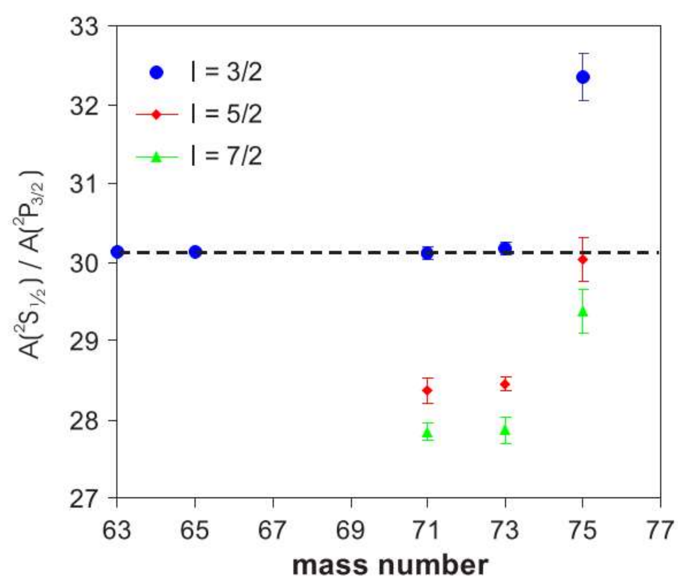
K.T. Flanagan et al., Phys. Rev. Lett. 103 (2009) 142501

- In-source laser spectroscopy at ISOLDE used for a low-resolution probe of ^{75}Cu HFS
- High-resolution collinear laser spectroscopy resolved both atomic ground and excited state HFS
- The ratio of HF factors of the upper and lower state should be constant across an isotopic chain…nuclear spin is $5/2^+$ at ^{75}Cu

and by improving the experimental sensitivity by ×300…



R.P. de Groote et al., Phys. Rev. C 96 (2017) 041302(R)



Nuclear magnetic moments

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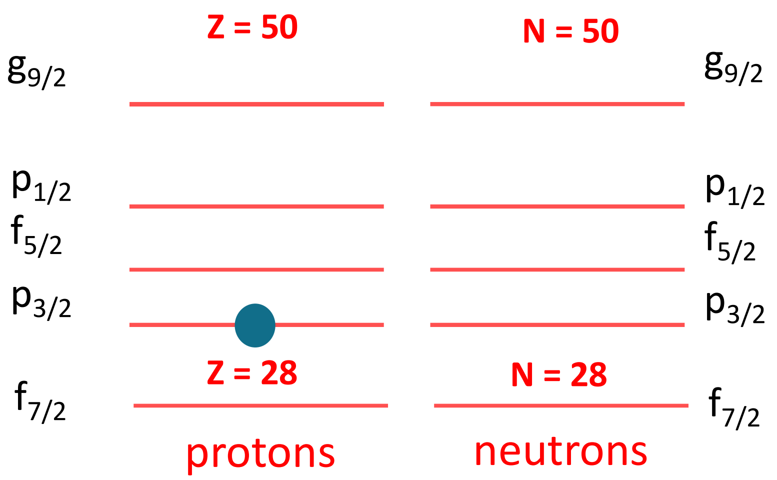
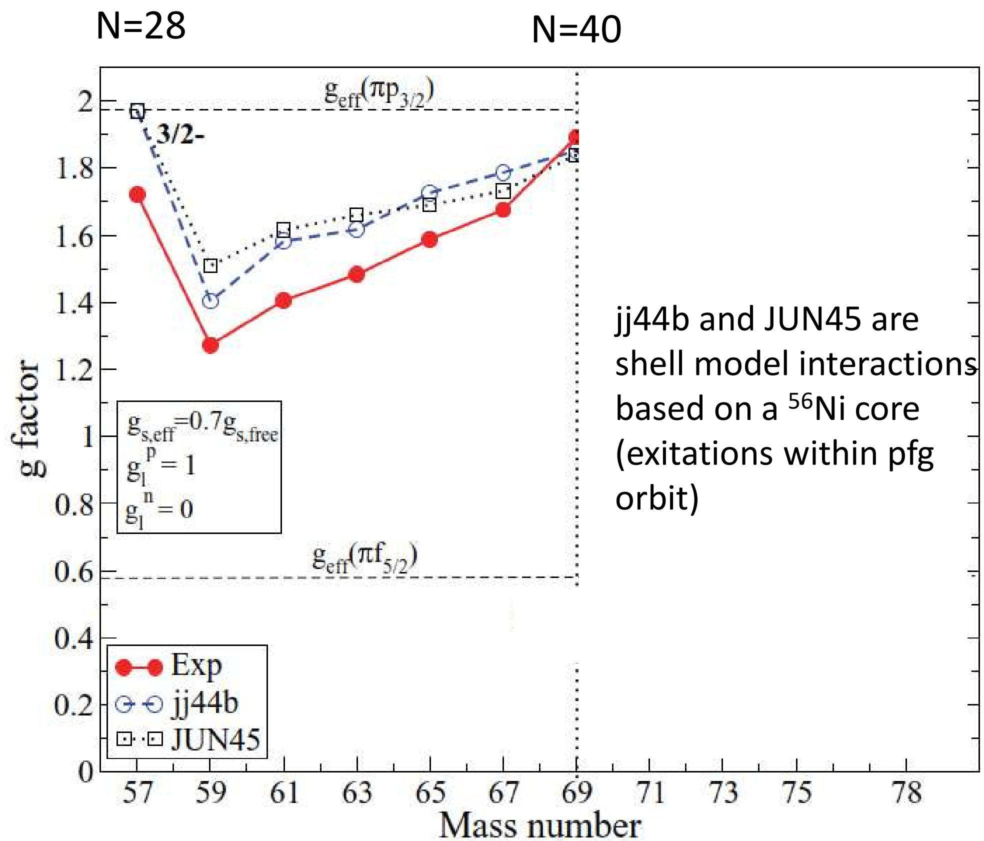
- Nuclear moments provide an exceptionally sensitive probe of the nuclear wave function and the different orbitals involved, for example, during the onset of deformation (collectivity)



- From A=57-79, neutrons fill the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals
- g factor reveals the orbit occupied by the unpaired proton
- At ^{57}Cu (*N*=28) and ^{69}Cu (*N*=40), the exp. g factor is close to the effective single-particle value for the $\pi p_{3/2}$



P. Vingerhoets et al., Phys. Rev. C 82 (2010) 064311

Magnetic and quadrupole moments

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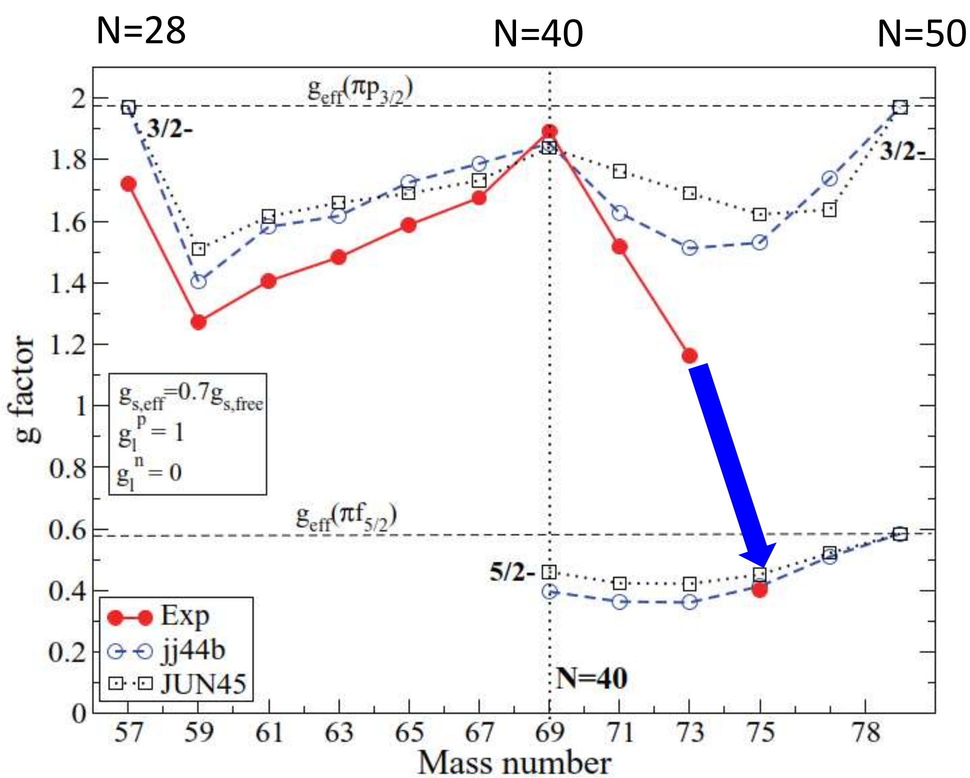

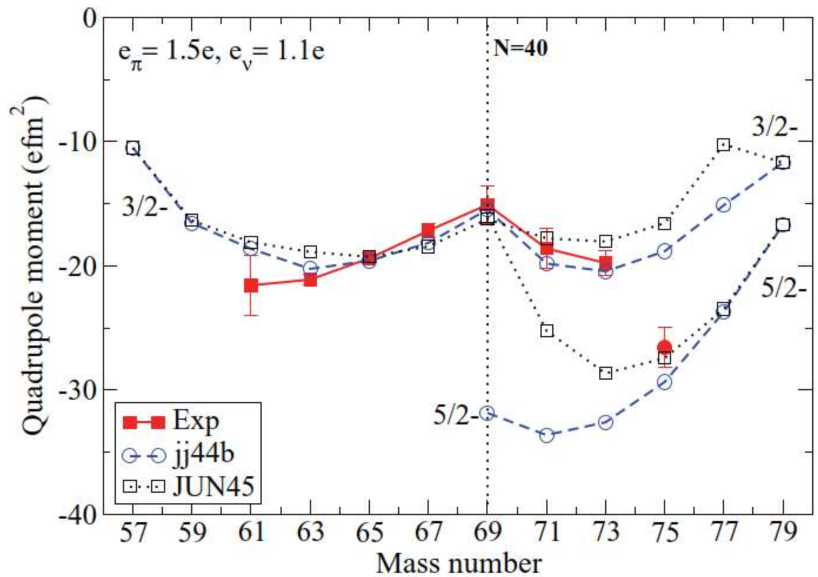

P. Vingerhoets et al., Phys. Rev. C 82 (2010) 064311

- The g factor of ^{73}Cu is not reproduced by the two shell model interactions! This indicates "missing physics" in the theory
- The electric quadrupole moment is an ideal parameter to probe collectivity – does this evolve with additional neutron correlations far from stability?
- One can also compare experimental quadrupole moments with shell model predictions

What if we expand the shell model "space"?

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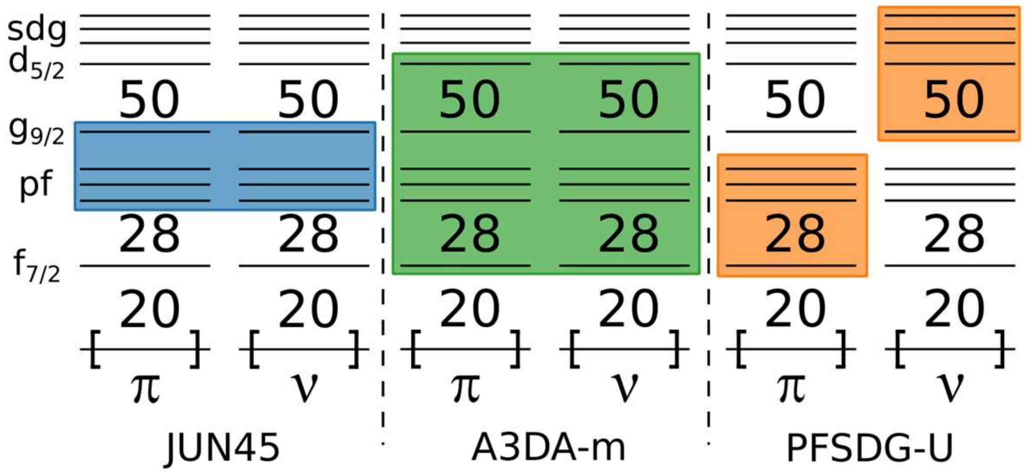
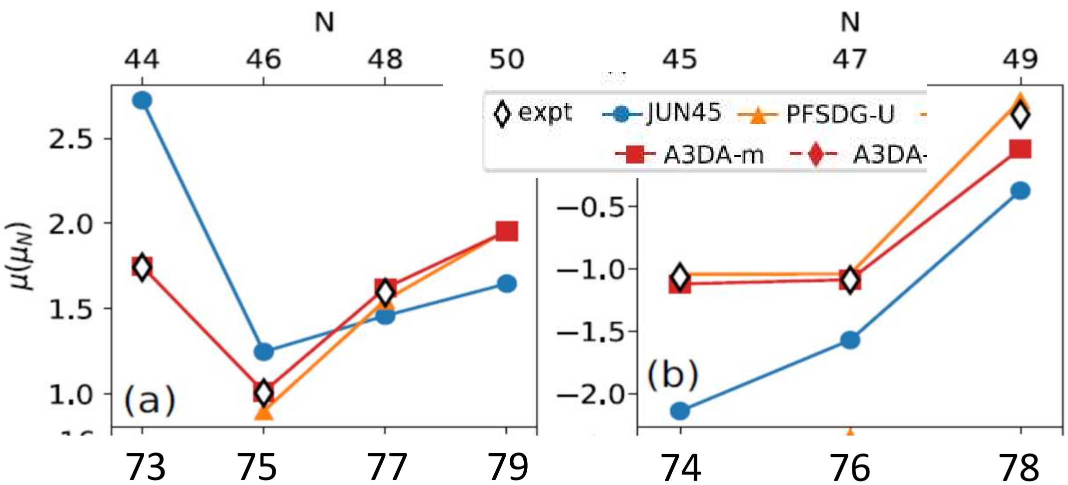
By opening the model space we can allow for additional "residual correlations" which may account for the "missing physics"…



JUN45: pf shell and $g_{9/2}$ between N,Z=28 and N,Z=50

A3DA-m: include $f_{7/2}$ below 28, $d_{5/2}$ above 50

PFSDG-U: full negative parity pf shell for protons, full positive parity sdg shell for neutrons



- Magnetic dipole moments are a particularly sensitive observable in this shell model picture
- No good agreement with JUN45
- Excellent agreement with A3DA-m/ PFSDF-U

R.P. de Groote et al., Phys. Rev. C 96 (2017) 041302(R)

Probing the nuclear size and shape

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Reminder: isotopic shifts

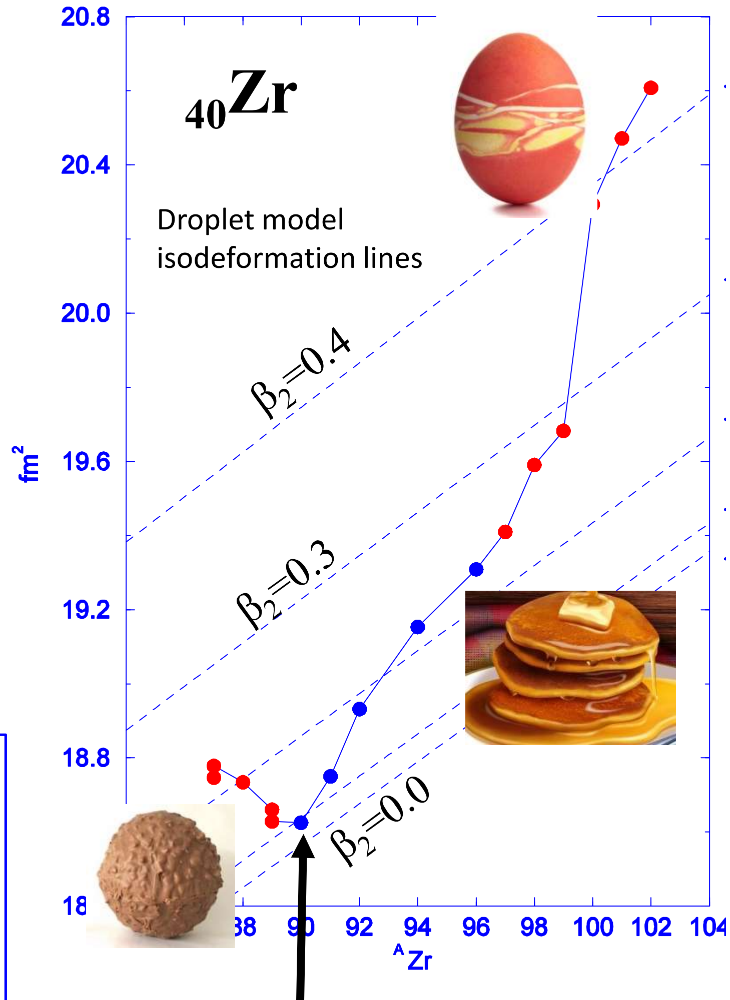
$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \boxed{\delta\langle r^2\rangle^{A,A'}}$$

What can the charge radii tell us?

$$\langle r^2\rangle = \langle r^2\rangle_{sph}\left(1+\frac{5}{4\pi}\left(\langle\beta_2^2\rangle+\ldots\right)\right)+3\sigma^2$$

Size (droplet model) — Shape (Quadrupole term) — Diffuseness (assumed constant)

- The $\delta\langle r^2\rangle$ arising from the addition of 1 neutron is ~0.07 fm^2. If the shape changes from $\langle\beta^2\rangle$ = 0 to 0.1, an order of magnitude larger increase in $\delta\langle r^2\rangle$ is expected.
- Nuclear deformation also probed via other nuclear-based spectroscopy techniques
- Higher order deformation (eg octupole β_3), higher order radial moments (eg r^4) would be new territory!



N=50 shell closure

Yttrium – different shapes and sizes

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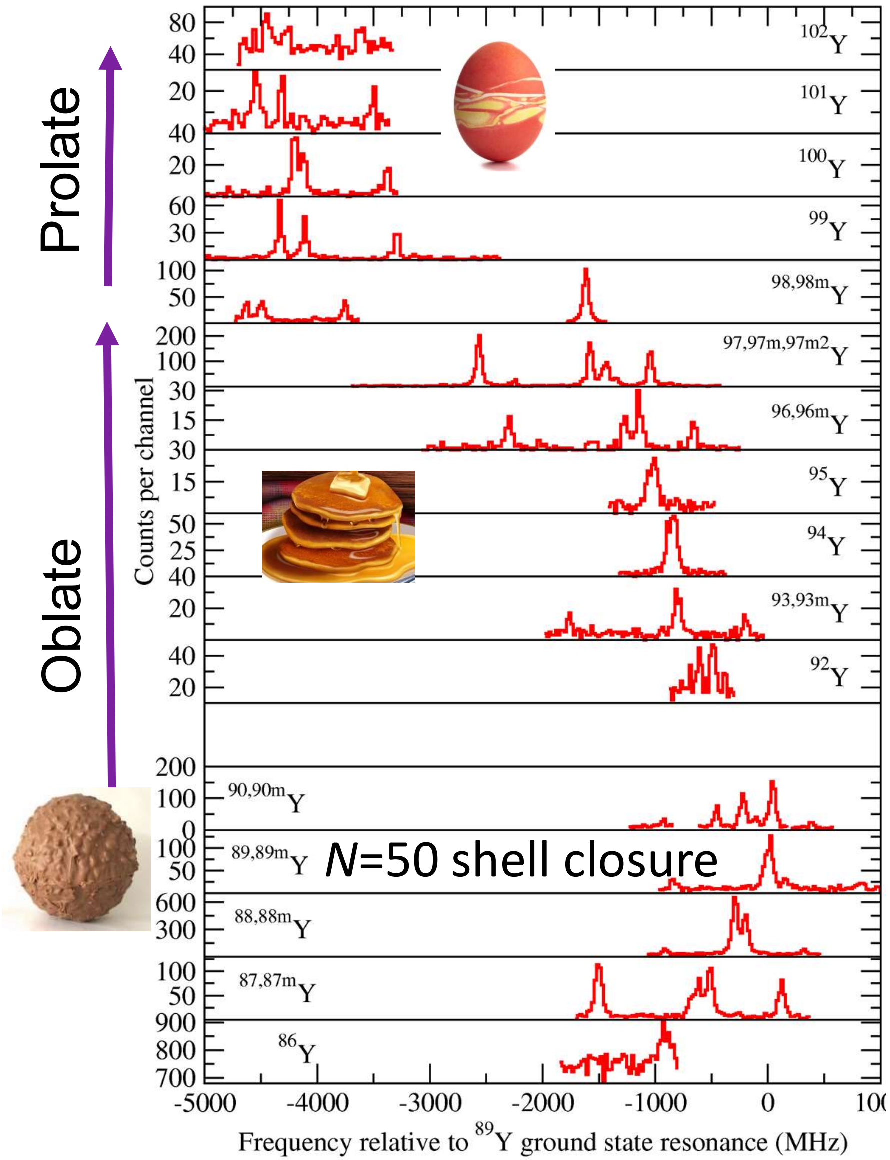
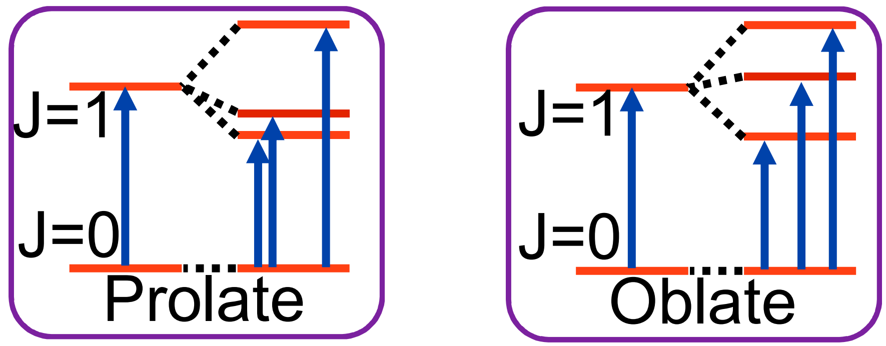


3 peaks maximum for each nuclear state



- Yttrium contains many isomeric (long-lived) nuclear states
- Quadrupole moments indicate a shape transition from (weakly) oblate to (strongly) prolate

$$Q_0 \approx \frac{5Z\langle r^2\rangle_{\mathrm{sph}}}{\sqrt{5\pi}}\langle\beta_2\rangle(1+0.36\langle\beta_2\rangle)$$

B. Cheal et al., Phys. Lett. B 645 (2007) 133

How "soft" or "rigid" are nuclei?

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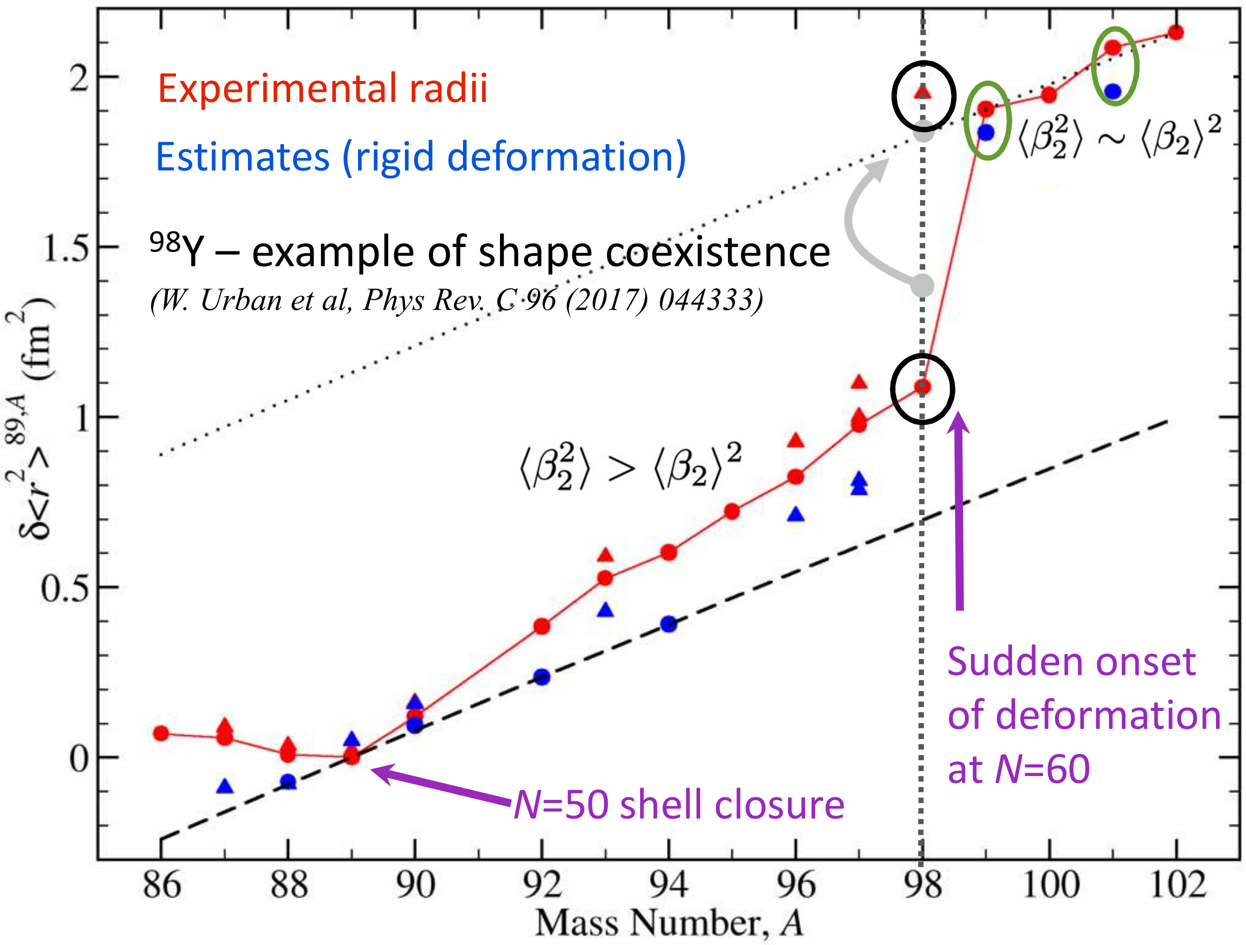
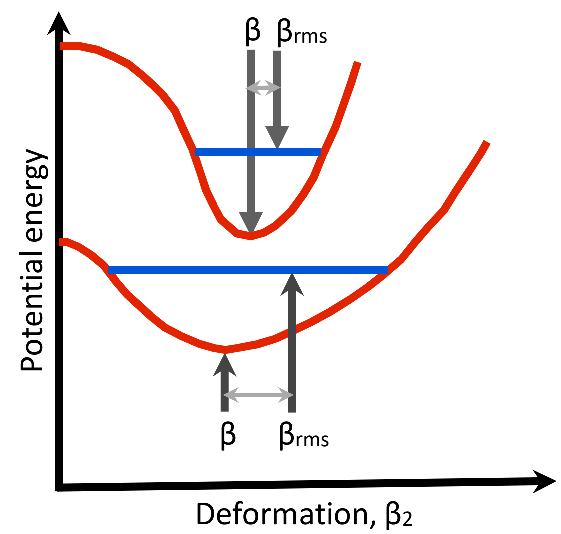


$$Q_s \rightarrow \langle\beta_2\rangle$$
$$\delta\langle r^2\rangle \rightarrow \delta\langle\beta_2^2\rangle$$



The difference between $<\beta_2>$ and $<\beta_2^2>$ gives the "softness" / "rigidity".

Charge radii systematics near Zr (Z=40)

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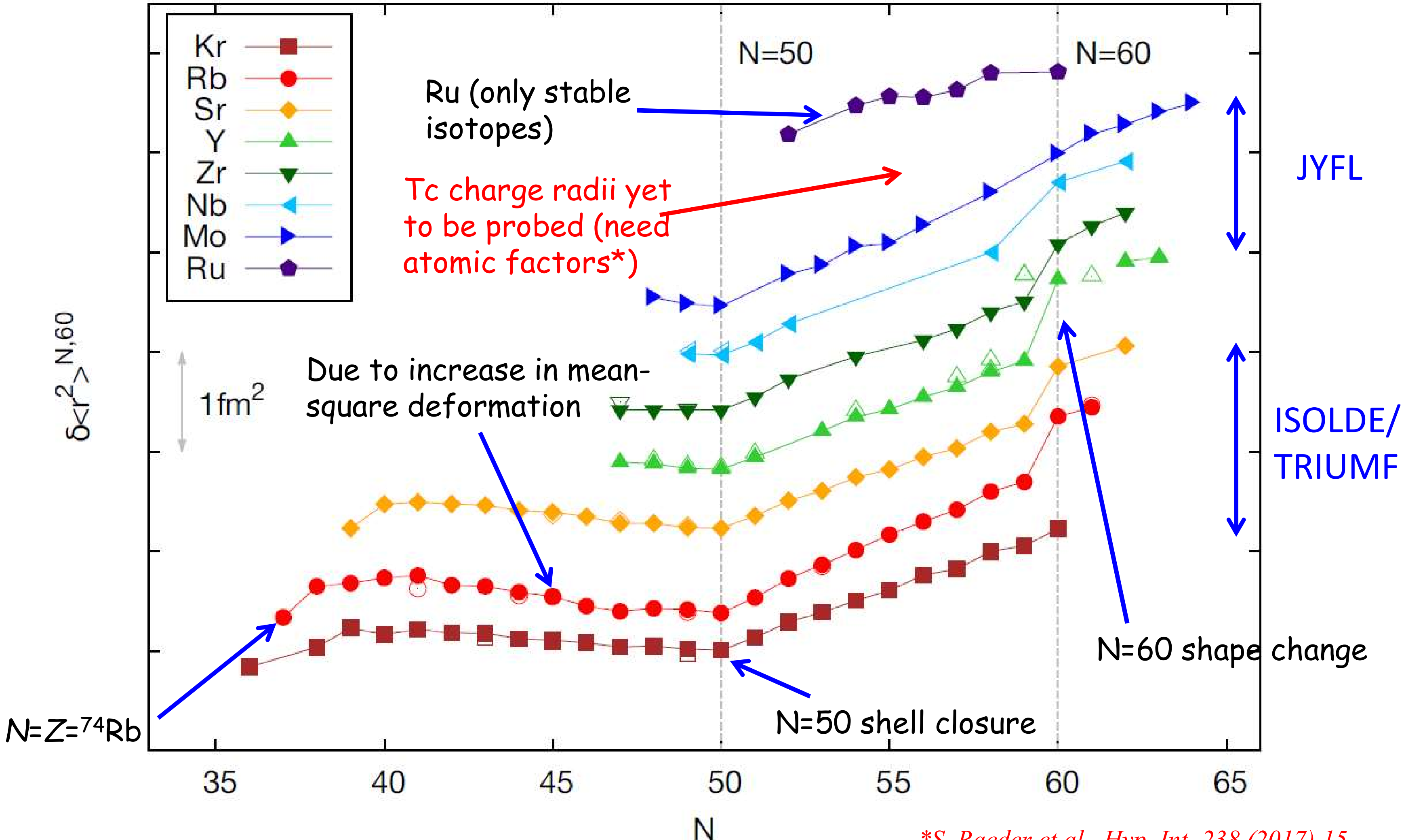

**S. Raeder et al., Hyp. Int. 238 (2017) 15*

P. Campbell, IM, and M. Pearson, PPNP 86 (2016) 127

Complementarity: the nuclear mass surface

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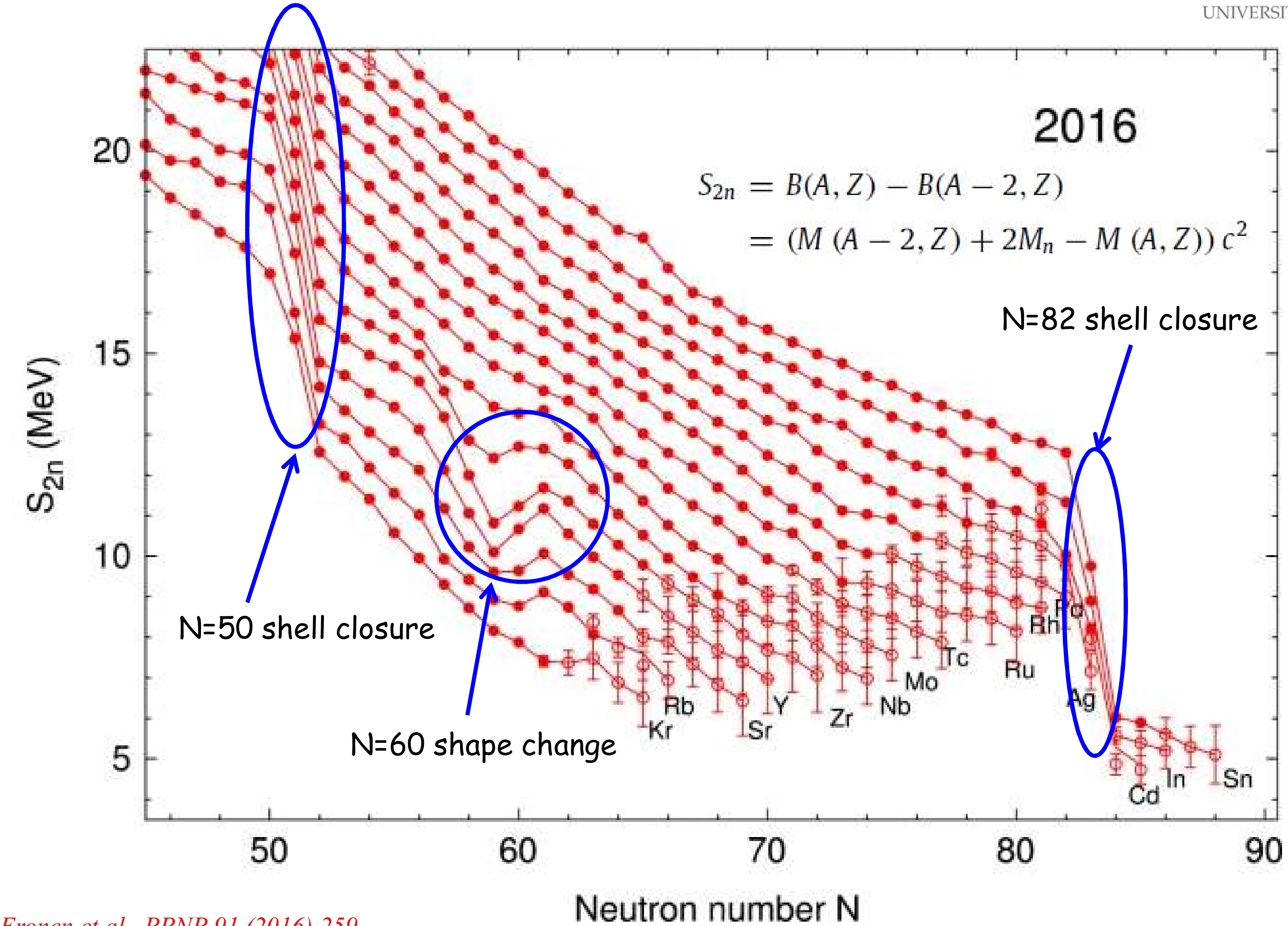

T. Eronen et al., PPNP 91 (2016) 259

Shape coexistence in the nuclear chart

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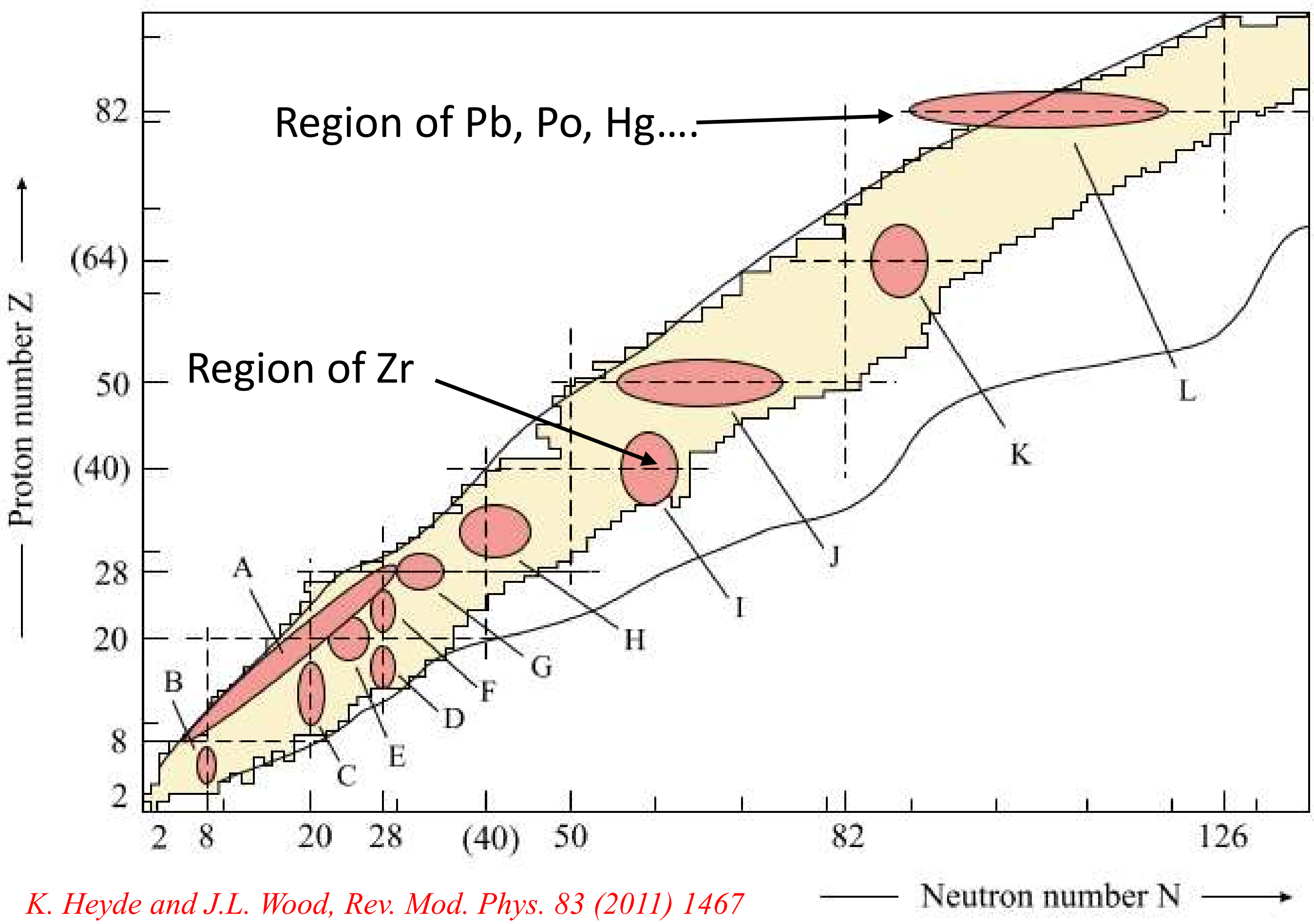
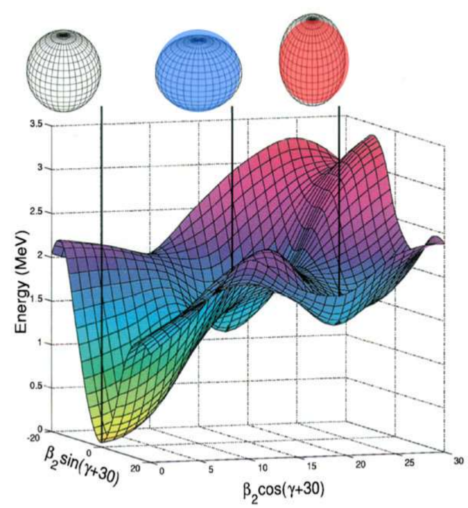
- ”Shape coexistence appears to be unique in the realm of finite many-body quantum systems”
- States with different shape/deformation at low energy
- Interplay between stabilizing effect of closed shells and mid-shells for proton-neutron interactions



K. Heyde and J.L. Wood, Rev. Mod. Phys. 83 (2011) 1467

Shell Model picture: Coexistence of “normal” and “intruder” structures

Mean field picture: Several minima in energy surface vs deformation



Staggering in the charge radii of Hg isotopes

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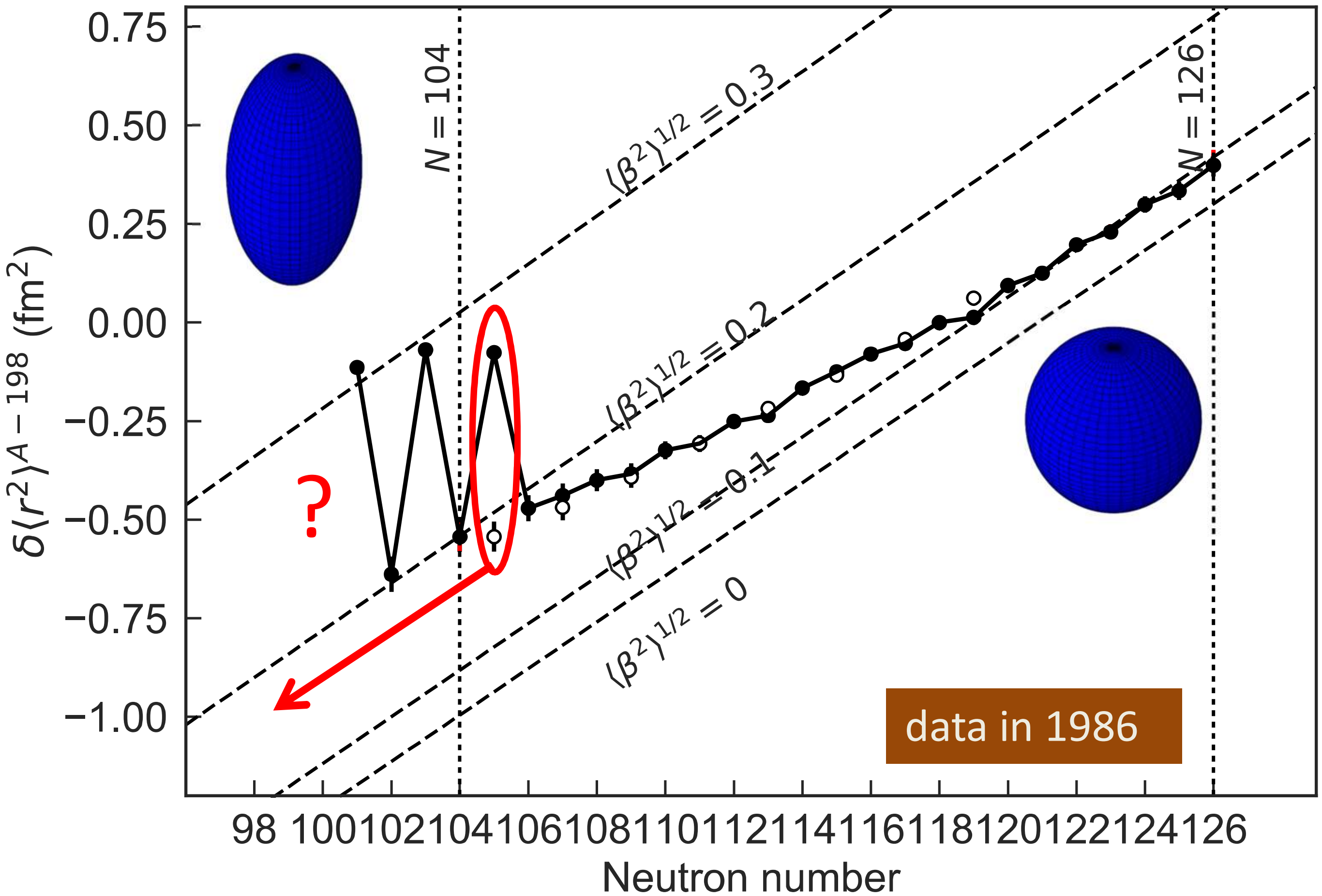
← *Neutron deficient* *Neutron rich* →



Huge increase in charge radius around the neutron mid-shell (N=104);

^{181,183,185}Hg

Shape coexistence established in ^{185}Hg!

J. Bonn et al., Phys. Lett. B 38 (1972) 308

G. Ulm et al., Z. Phys. A 325 (1986) 247

What is driving the staggering effect?

Filling in the picture: nuclear level systematics

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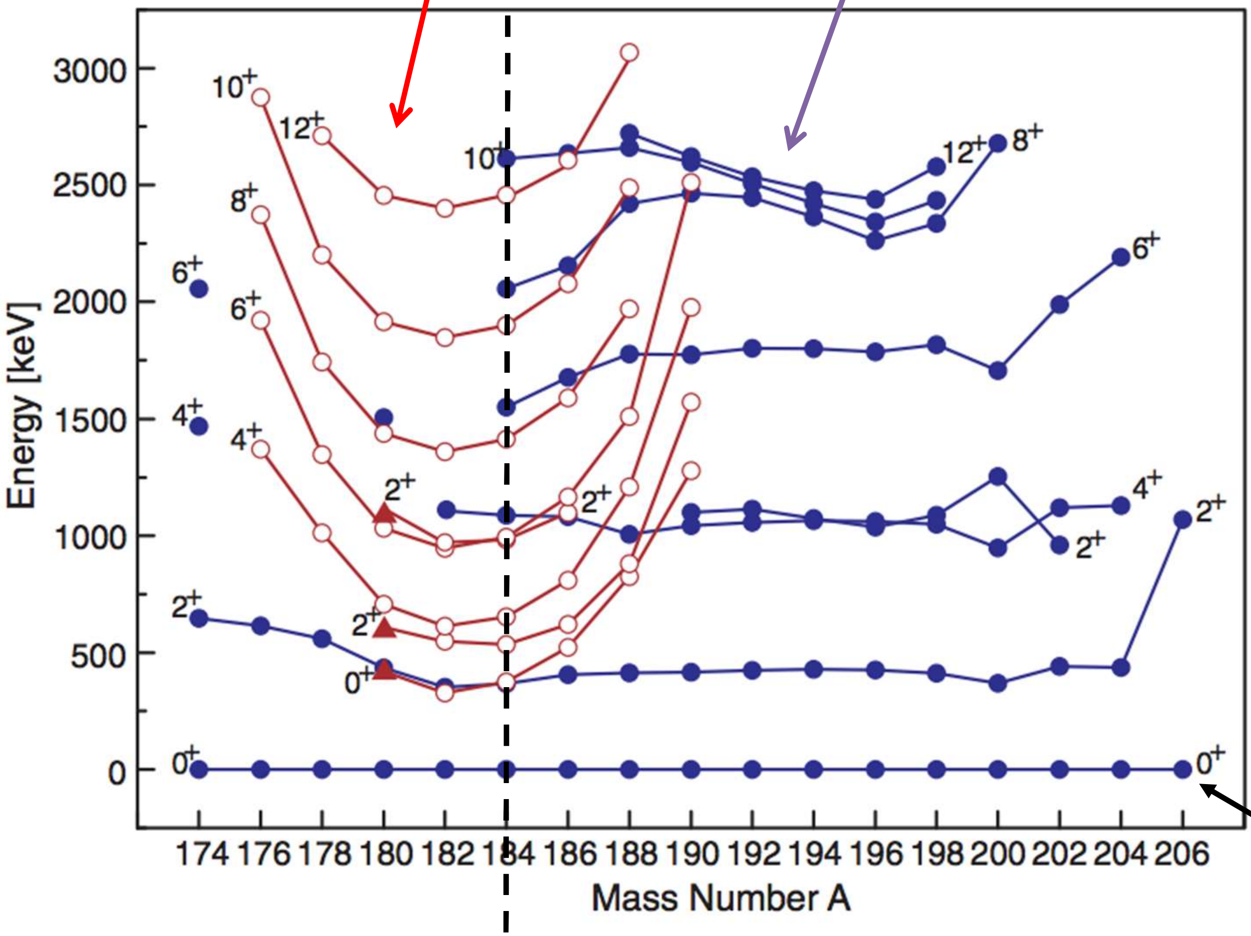
Prolate

Oblate



N=104 mid-shell

Coexistence of different bands in Hg isotopes

Prolate "intruder" states come down in energy towards minimum around *N=104* mid-shell region

Studied by many nuclear spectroscopy techniques

Ground state (probed by laser spectroscopy). Charge radius difference linked to the odd neutron driving deformation.

When does the staggering end?

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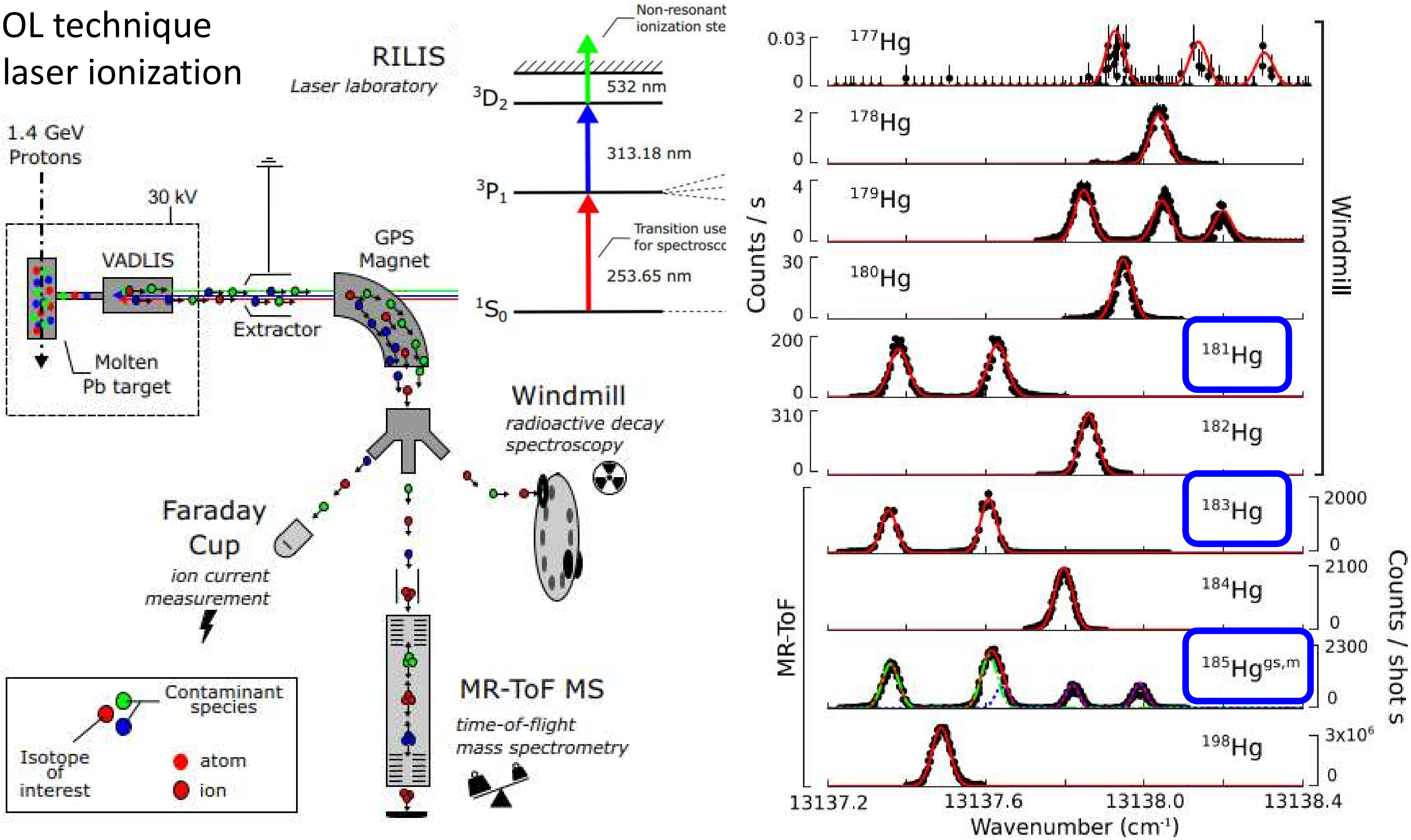
ISOL technique
+ laser ionization



Combining detection in three different experimental stations

B. Marsh et al., Nature Phys. 14 (2018) 1163
S. Sels et al., Phys. Rev. C 99 (2019) 044306

After 30 years of developments….

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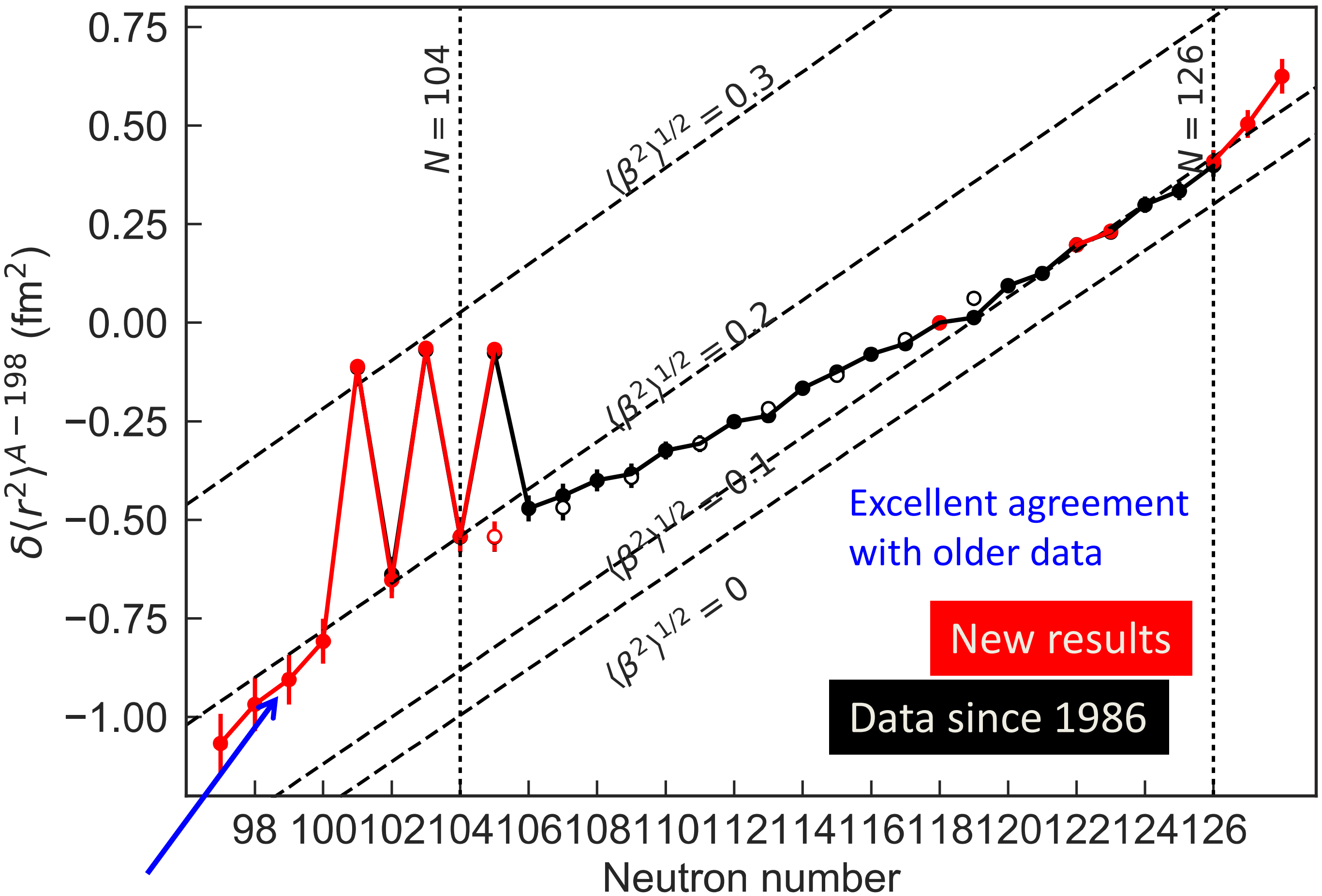

End-point of staggering observed, Hg isotopes return to more spherically-shaped trend.

Rich playground for testing theoretical calculations!

B. Marsh et al., Nature Phys. 14 (2018) 1163, S. Sels et al., Phys. Rev. C 99 (2019) 044306

Triple shape coexistence in ^{186}Pb

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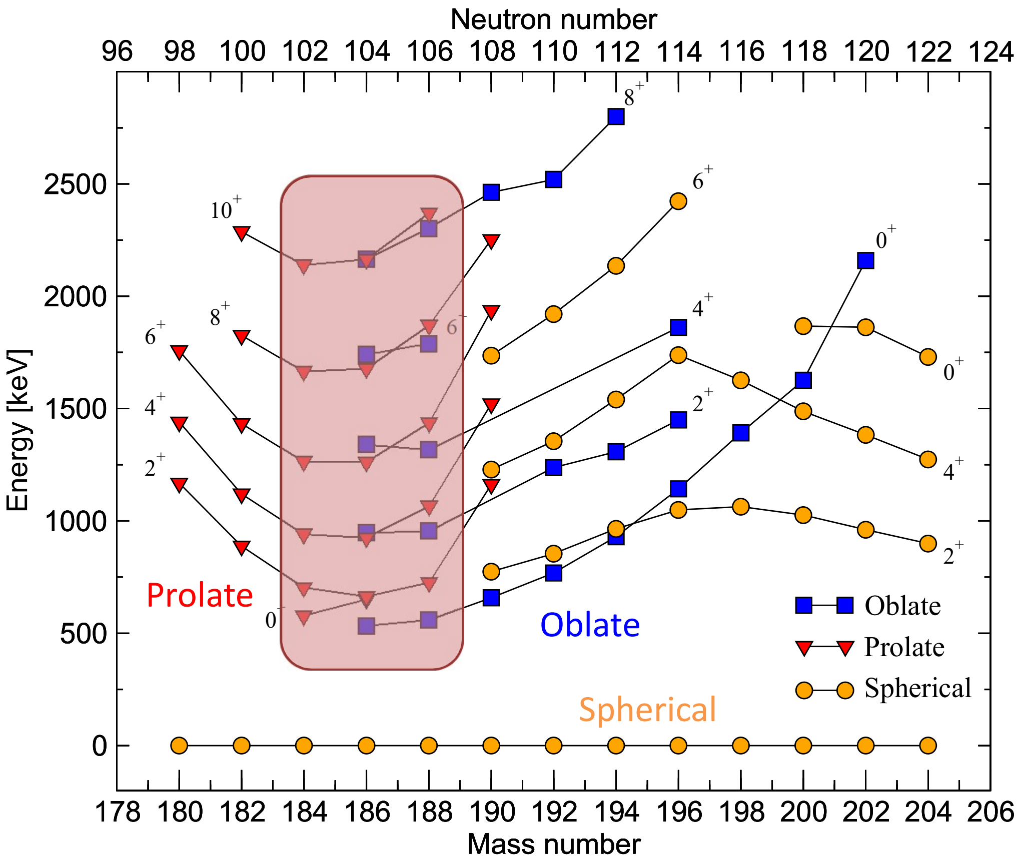
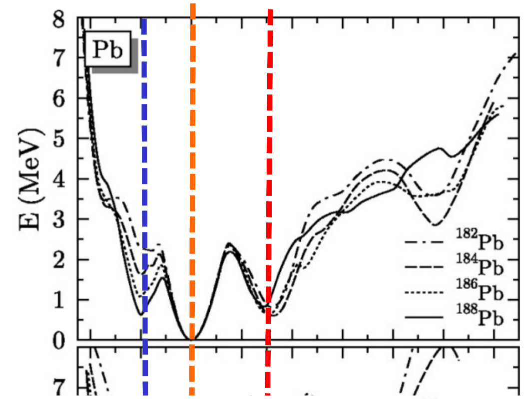
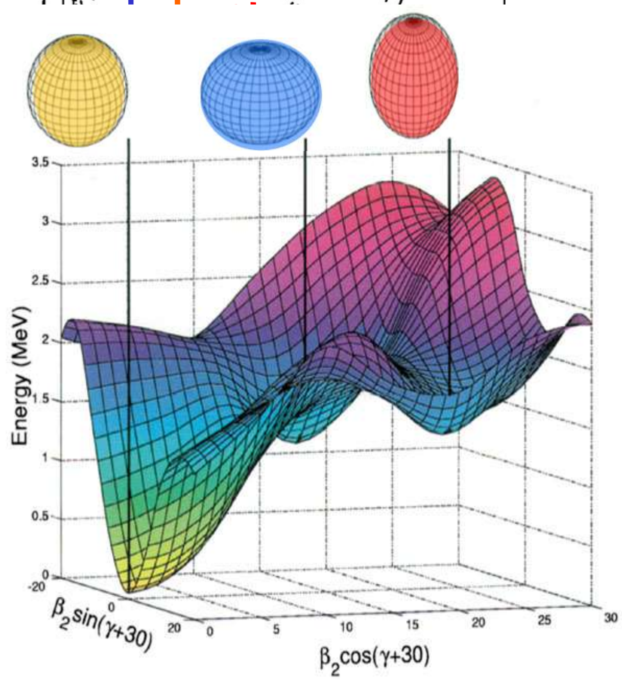


R. Julin et al., J. Phys. G 43 (2016) 024004





Different 'shapes' of an atomic nucleus (**spherical, prolate, oblate**) coexist at similar excitation energies.

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

Charge radii in the mid-shell region around Pb

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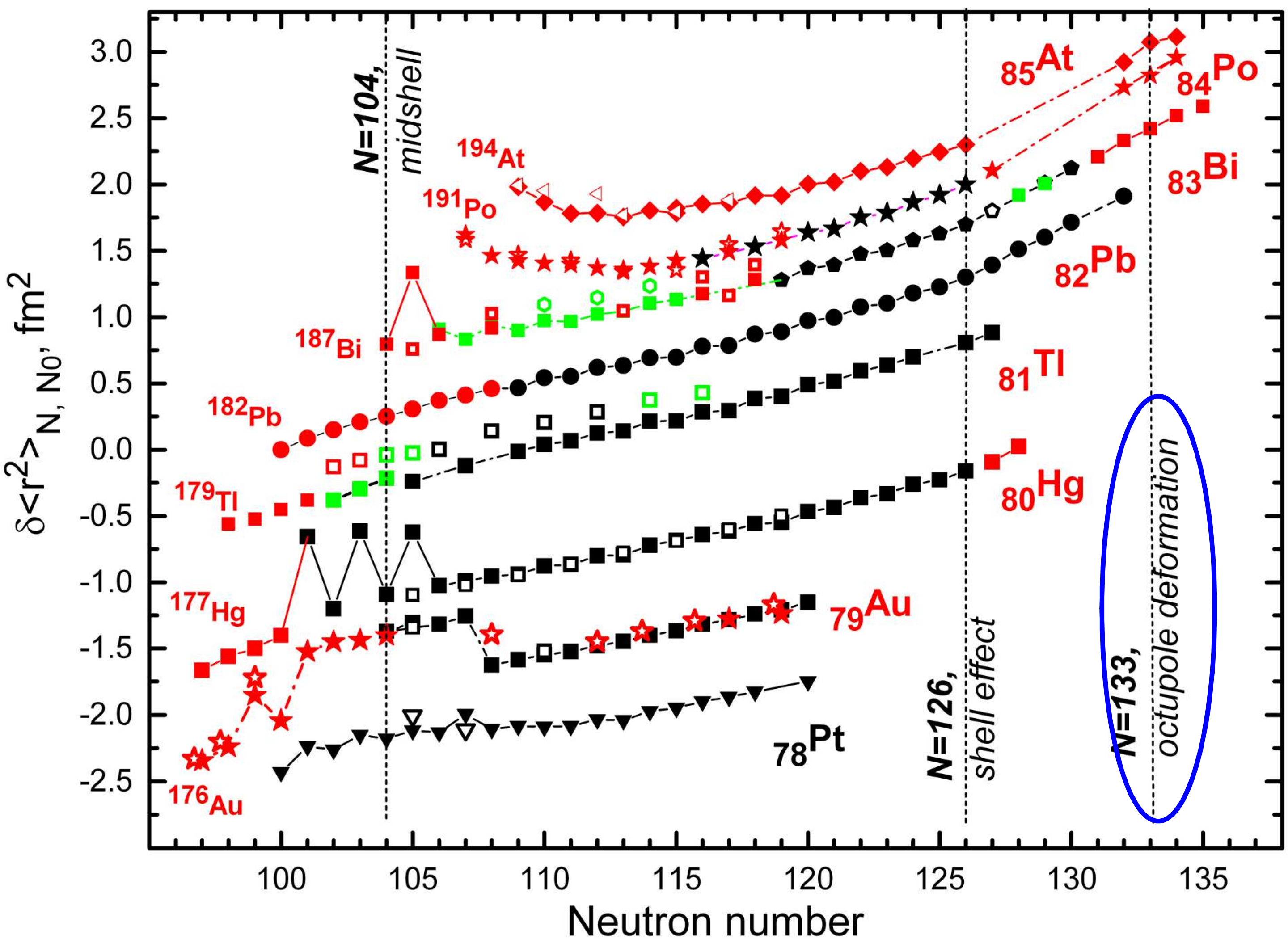
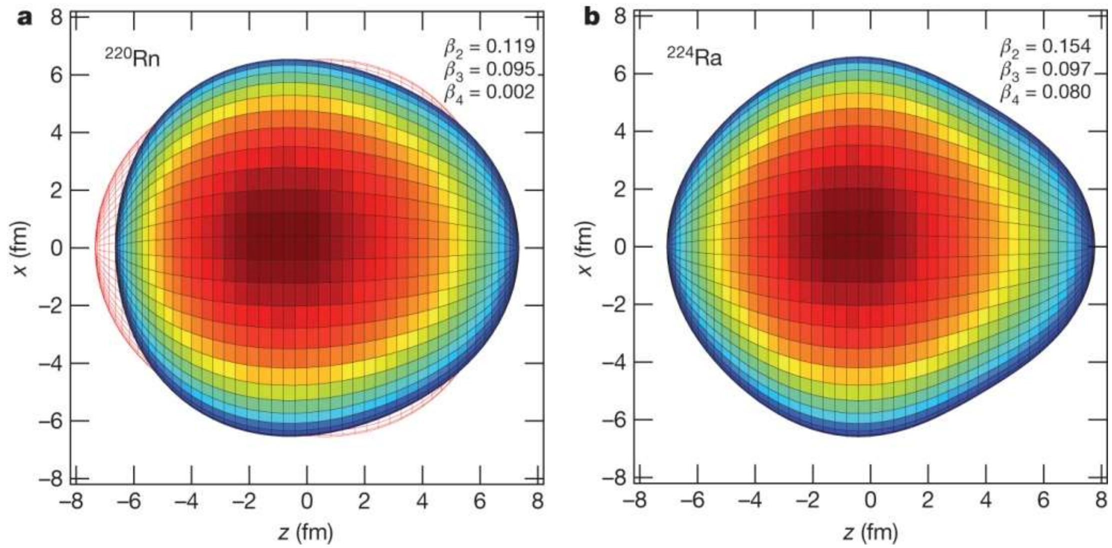


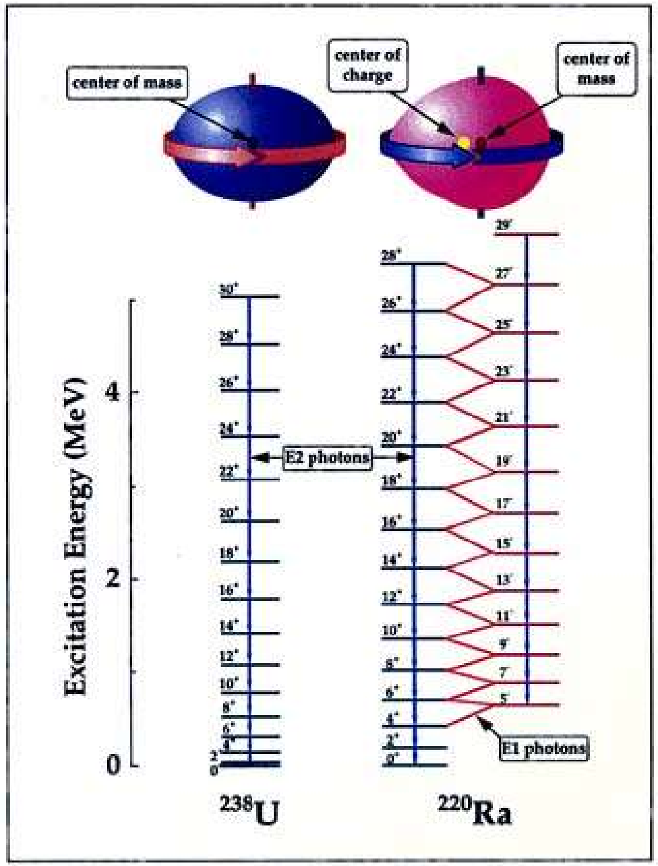
Pb ground states remain essentially spherical; evidence for shape staggering in Bi; "kink" in the N=126 shell is of topical interest (W. Nöertershäuser).

Probing more exotic deformations?

^{220}Rn ^{224}Ra



*L.P. Gaffney et al. Nature **497** (2013) 199*



- Strong evidence that unstable atomic nuclei can assume octupole (pear) shapes
- Isotopes of Rn, Ra, Th and U are predicted to have the strongest octupolar ”correlations”
- Constraint of candidates for experimental studies of electric-dipole moment (EDM), and thus existence of physics beyond the standard model (G. Neyens)

Top 10 breakthrough in physics in 2013 (Physics World)

“Pear-shaped nuclei discovery challenges time travel hopes”

Octupole deformation and charge radii?

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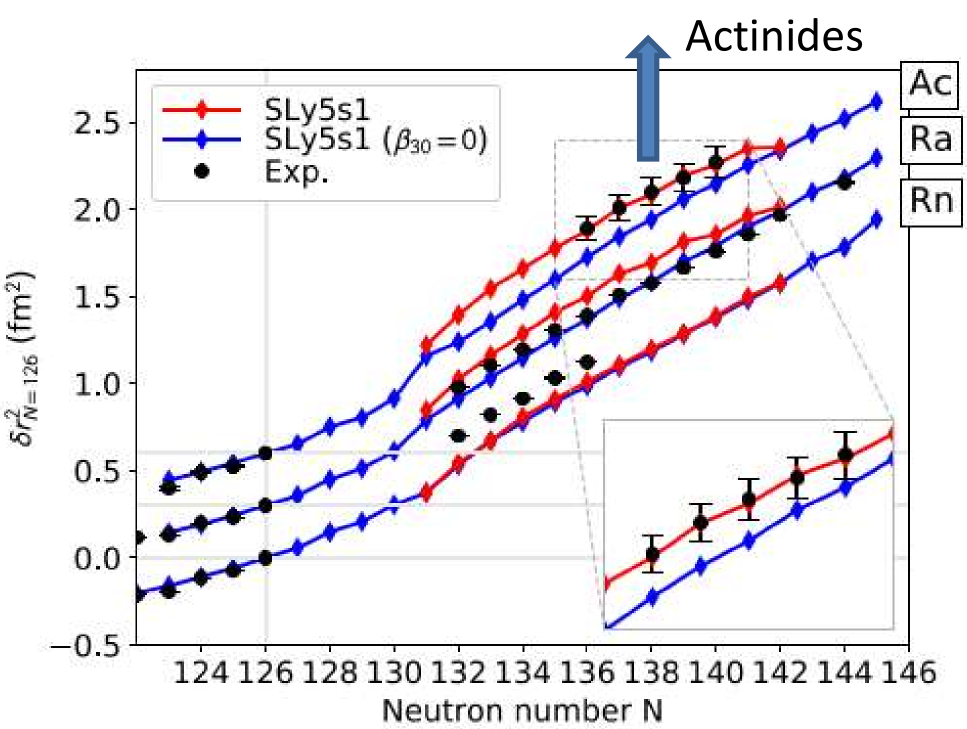
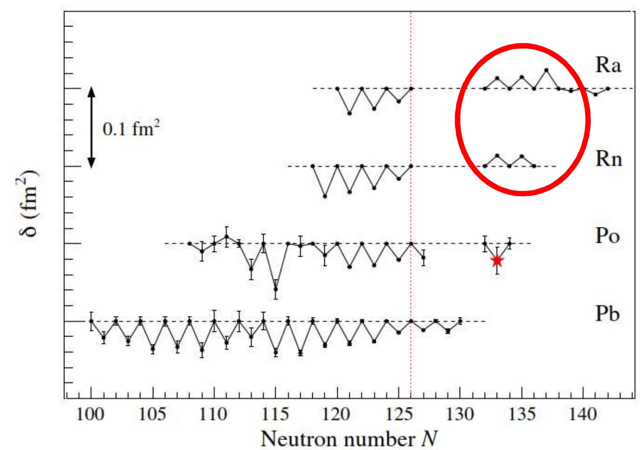
$$\langle r^2\rangle = \langle r^2\rangle_{sph}\left(1+\frac{5}{4\pi}\left(\langle\beta_2^2\rangle+\langle\beta_3^2\rangle+\cdots\right)\right)+3\sigma^2$$



E. Verstraelen et al., Phys. Rev. C 100 (2019) 044321

M. Bender, contribution to "Workshop on Laser Spectroscopy as a tool for Nuclear Theories" (Oct. 2019)

- Static octupole deformation can be found up to uranium
- Potential impact on magnetic dipole moments
- Reversal of odd-even staggering in charge radii maybe correlated to octupole deformation…
- New experimental and theoretical efforts in the future to access and study neutron-deficient actinide isotopes



D. Fink et al., Phys. Rev. X 5 (2015) 011018

Summary

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- Laser spectroscopy combined with radioactive ion beams: a powerful tool providing access to fundamental ground (and isomeric) state nuclear structure, complementary to other nuclear spectroscopic techniques but free from nuclear model dependencies
- Extract nuclear spins, magnetic & electric properties, charge radii…
- Contributes to answering, for example, questions of emergence of collective behavior (shape evolution) of nuclei and the re-ordering of quantum states

- Efficiency, selectivity and sensitivity of our techniques are critical to push to the most exotic nuclei (eg lightest, heaviest elements…)
- Critical dialogue with atomic theorists (atomic factors…) as well as nuclear theorists (interpretation of the experimental observables)
- Sensitivity to higher order deformation, moments, r^4 term?

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& thanks for your attention!