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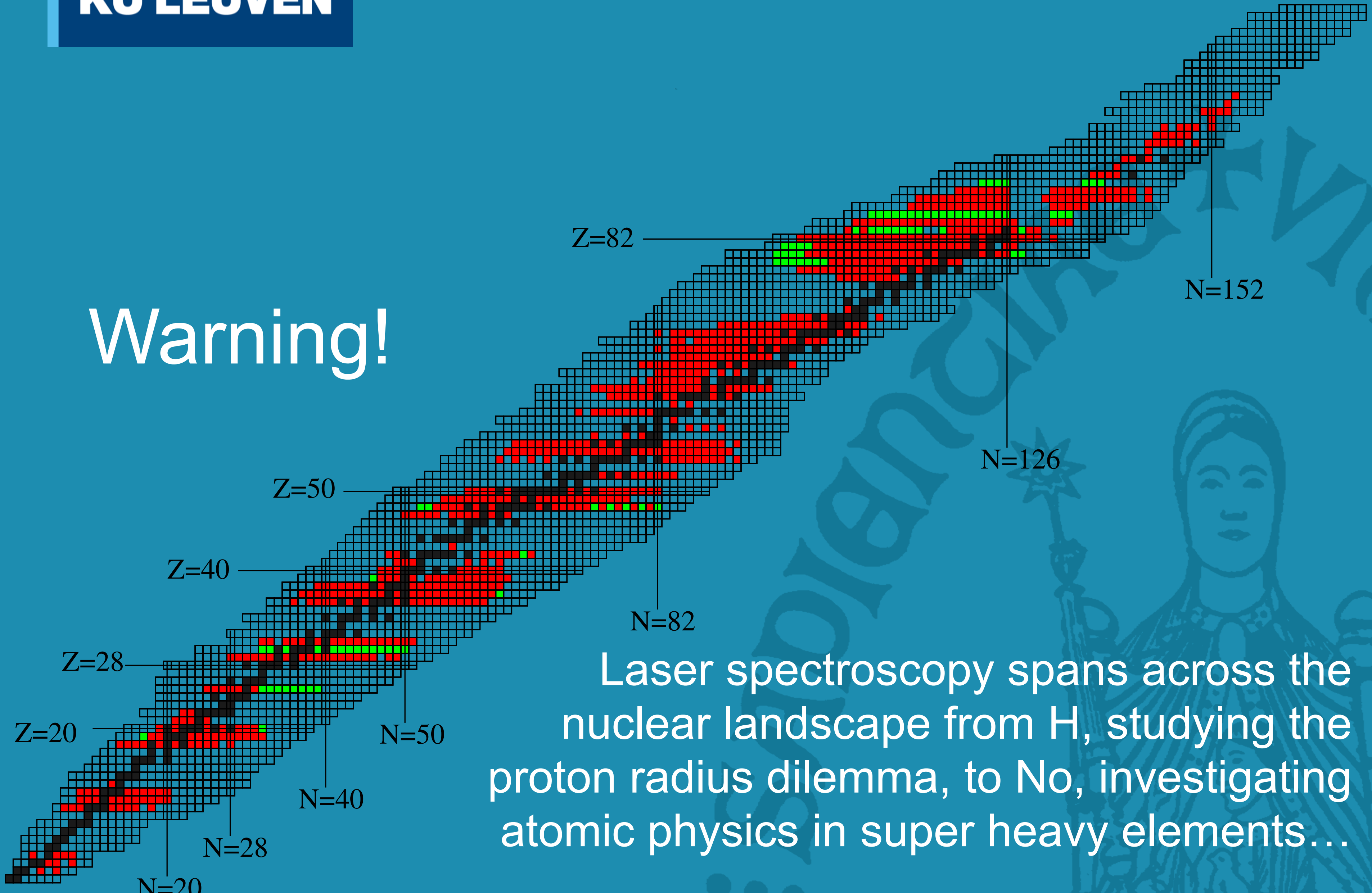
Nuclear charge radii and shape coexistence

Prof Thomas Elias Cocolios

ESNT Workshop - 23-27 Oct 2017

Warning!



Laser spectroscopy spans across the nuclear landscape from H, studying the proton radius dilemma, to No, investigating atomic physics in super heavy elements…

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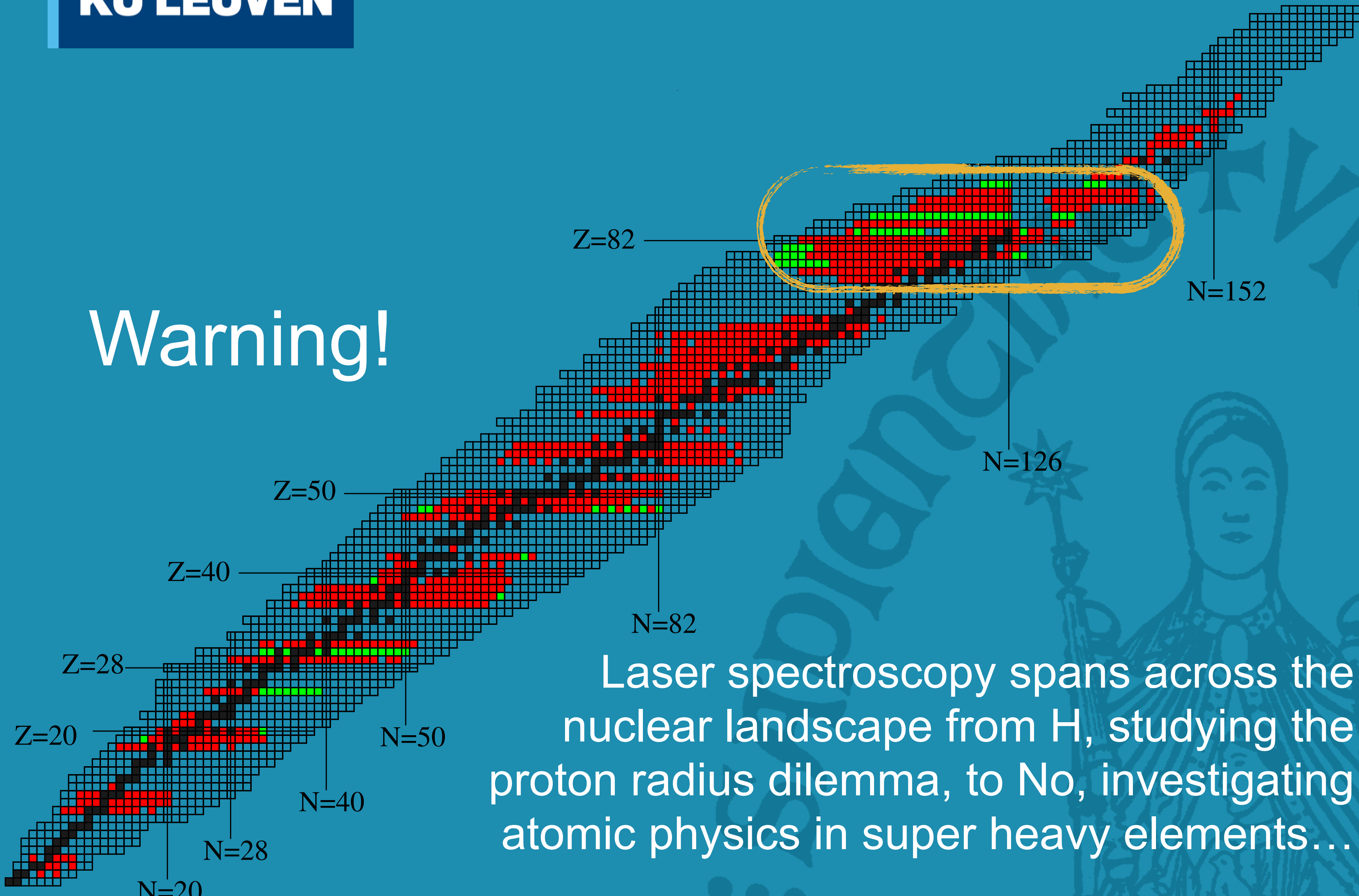
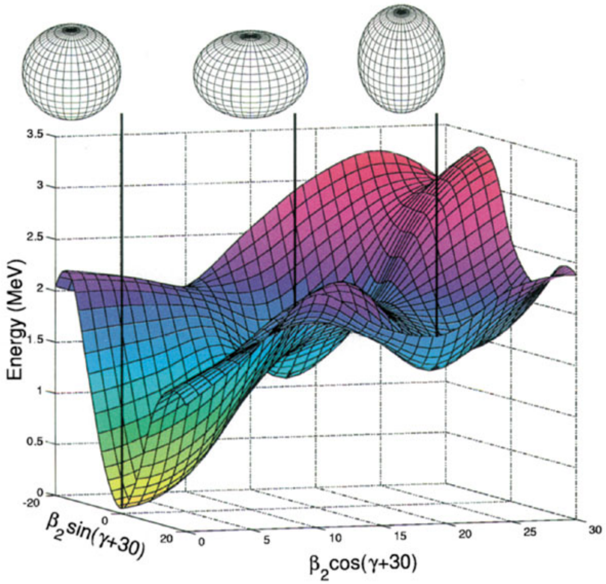
Warning!



Laser spectroscopy spans across the nuclear landscape from H, studying the proton radius dilemma, to No, investigating atomic physics in super heavy elements…

Outline



- Nuclear charge radii around Z=82
  - Laser spectroscopy studies
    - In-source laser spectroscopy
    - Collinear Resonance Ionization Spectroscopy
  - Looking at radii from another perspective
- Laser-assisted spectroscopy studies
  - Decay study of isomers
  - Mass measurements

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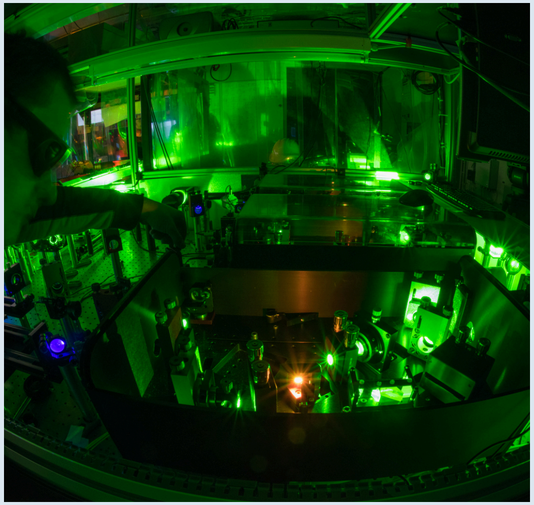
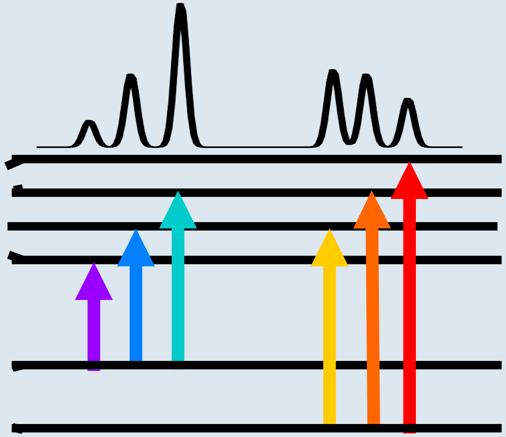


Laser spectroscopy

Shining light on different shapes



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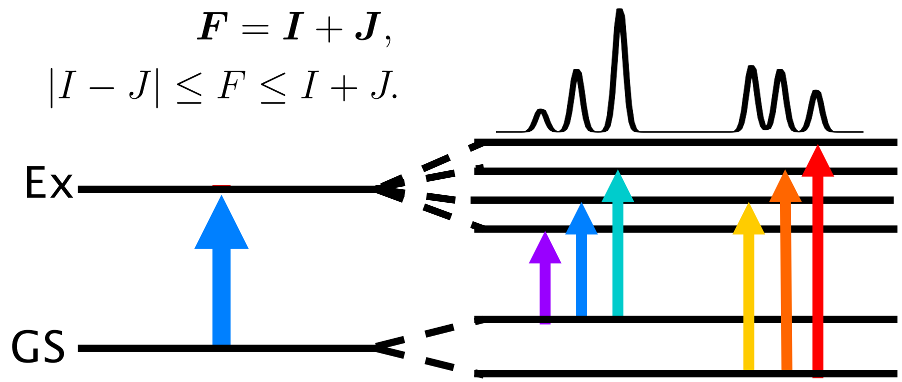
Fundamentals of laser spectroscopy

- Hyperfine structure
  - Nuclear spin
  - Magnetic dipole moment $\quad A = \frac{\mu B_0}{IJ}$
  - Electric quadrupole moment $\quad B = \frac{eQ}{4}\frac{\partial^2 V}{\partial z^2}$

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J},$$
$$|I - J| \leq F \leq I + J.$$



$$\Delta E = \frac{A}{2}K + \frac{B}{2}\frac{3K(K+1) - 2I(I+1)2J(J+1)}{2I(2I-1)2J(2J-1)}$$

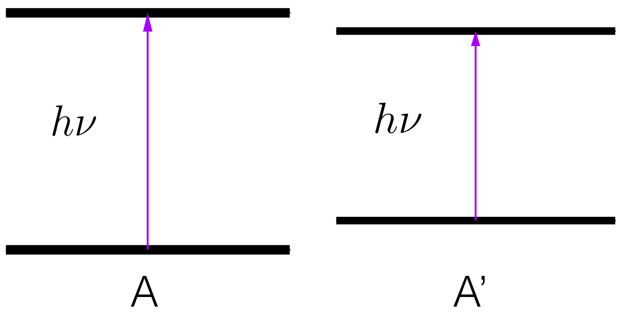
$$K = F(F+1) - I(I+1) - J(J+1)$$

Completely independent of nuclear / atomic models!

Measurements are relative to a reference…

Fundamentals of laser spectroscopy

- Isotope shifts
  - $\partial<r^2>$
  - Accessible over long chains of isotopes

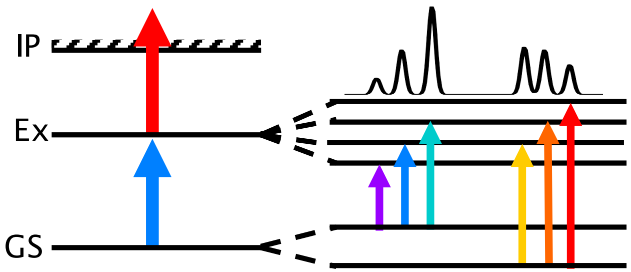


$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

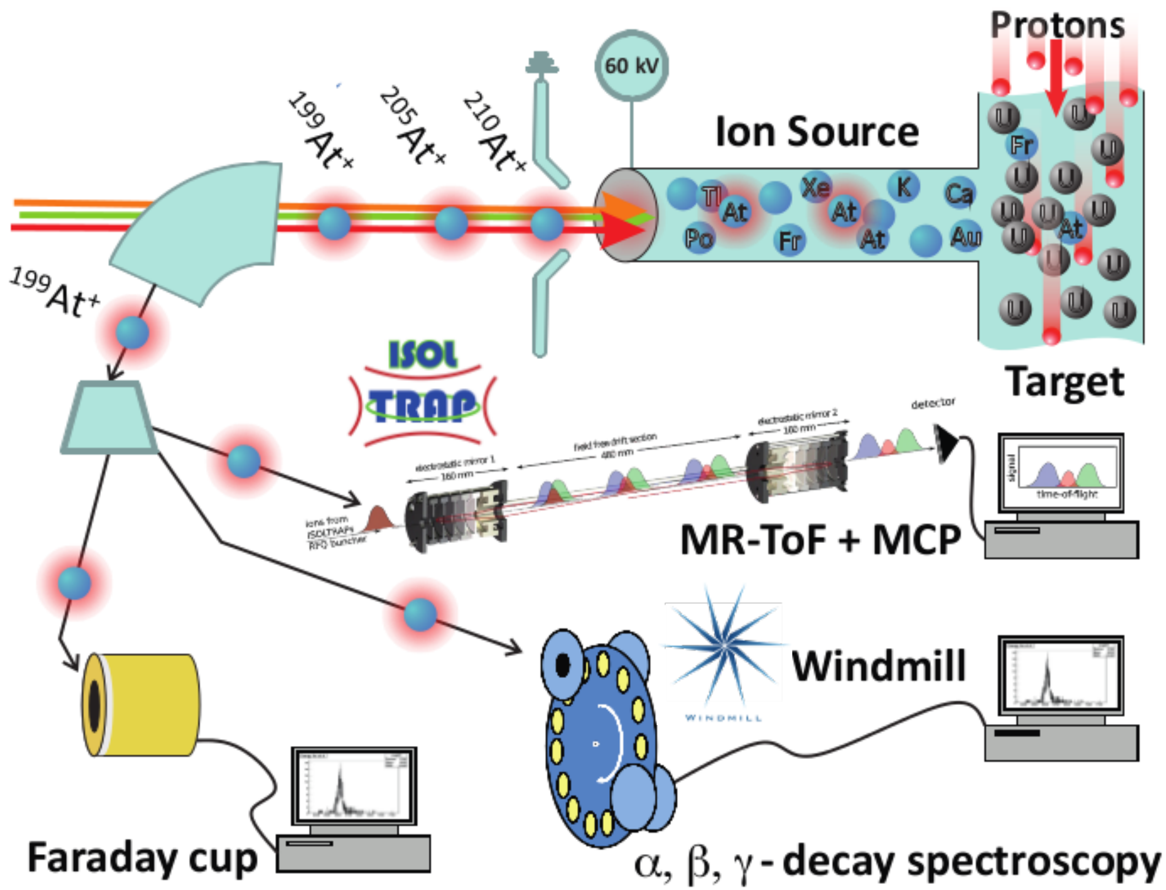
Completely independent of nuclear models!

Measurements are relative to a reference…
The atomic parameters are difficult to access experimentally
=> possible atomic model dependence

In-source laser spectroscopy



- Lasers are sent into the ion source to ionize the element of interest;
- One of the transitions is scanned and the yields are measured against frequency detuning;
- Mass separation and decay tagging are used to identified isotopes / isomers.



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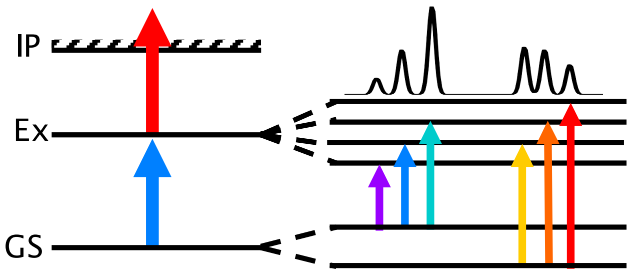
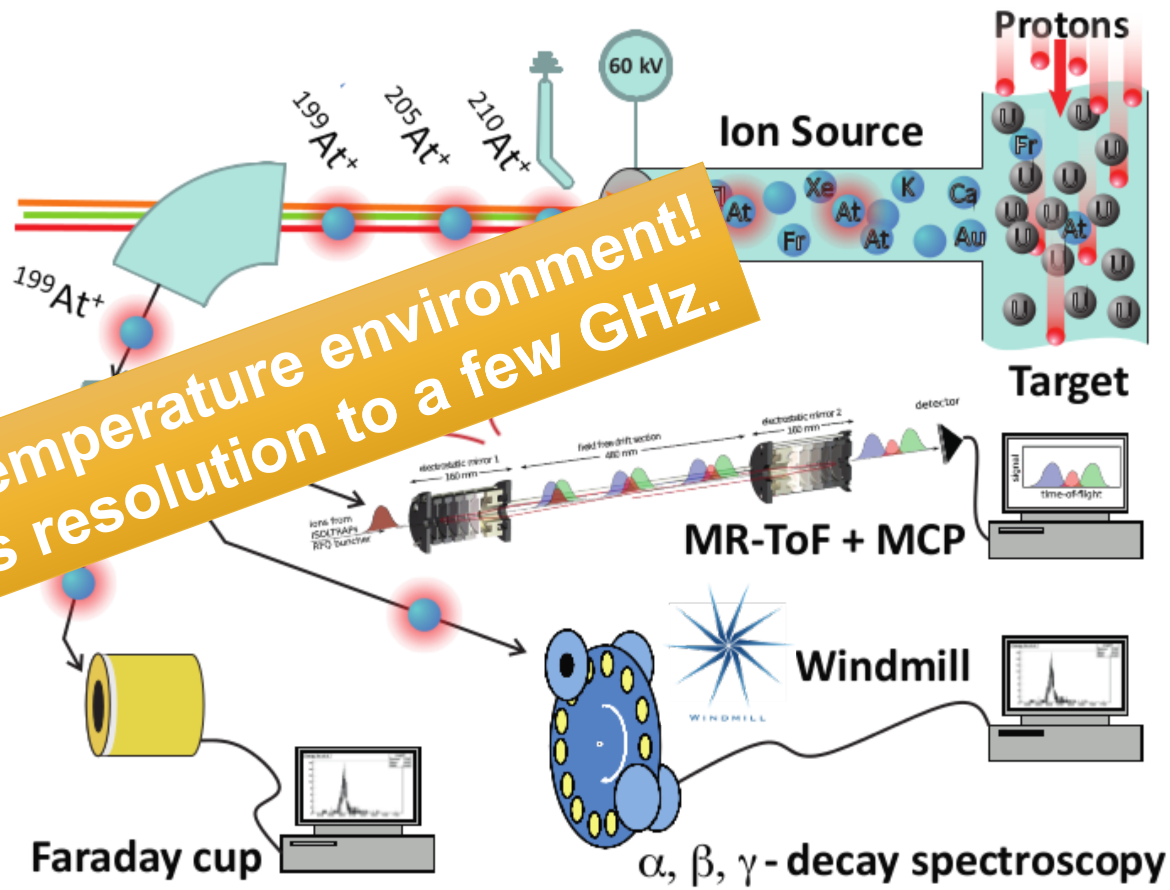
In-source laser spectroscopy



- Lasers are sent into the ion source to ionize the element of interest;
- One of the transition… scanned and the… are measured ag… frequency detuning;
- Mass separation and decay tagging are used to identified isotopes / isomers.

High temperature environment!
Limits resolution to a few GHz.



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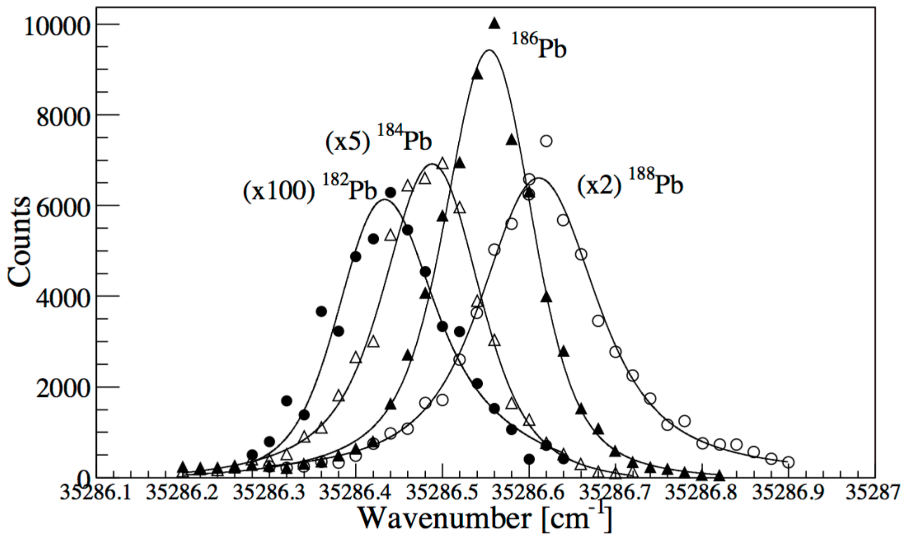
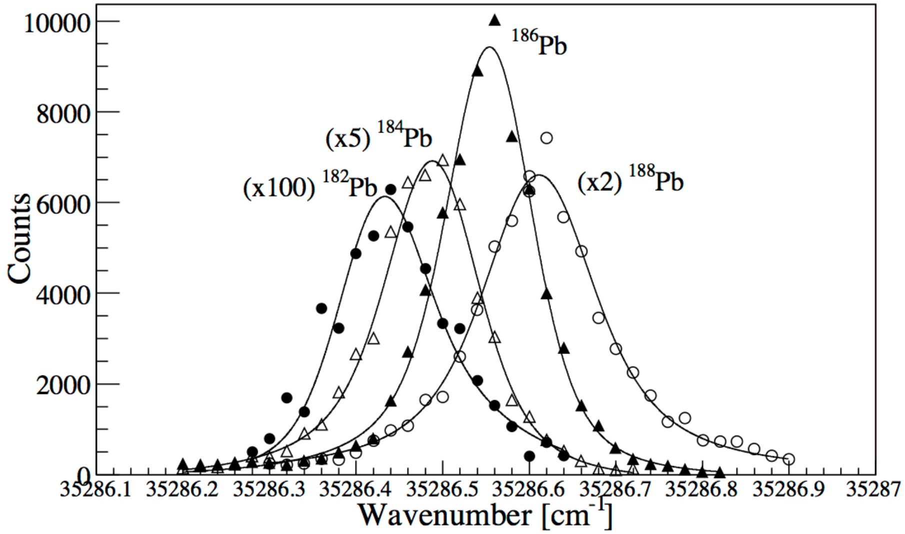
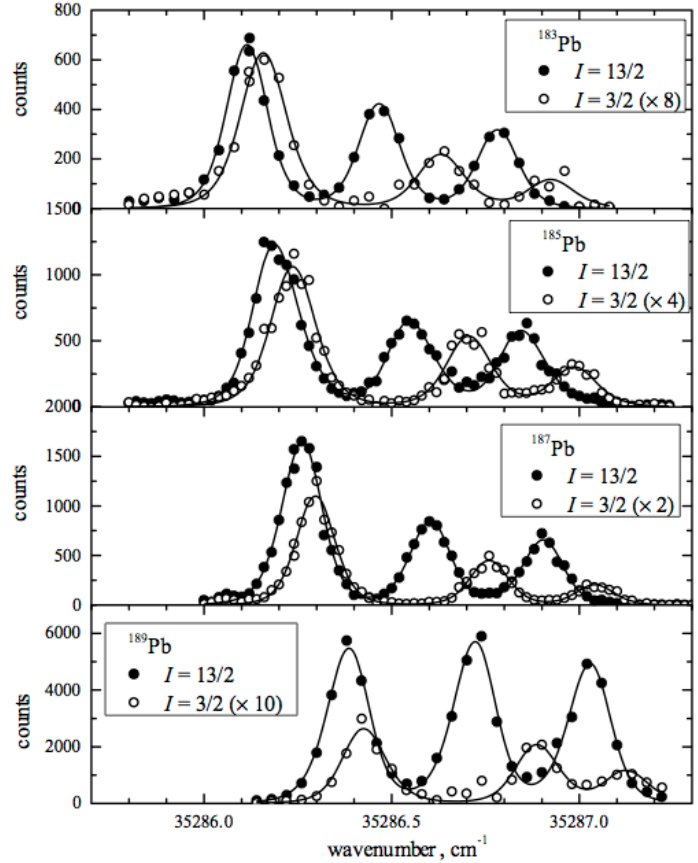
Rich data collection!



Pb: H. De Witte et al., PRL ***98****(2007)112502.*

Rich data collection!





*Pb: H. De Witte et al., PRL **98**(2007)112502;*
*M.D. Seliverstov et al., EPJA **41**(2009)315.*

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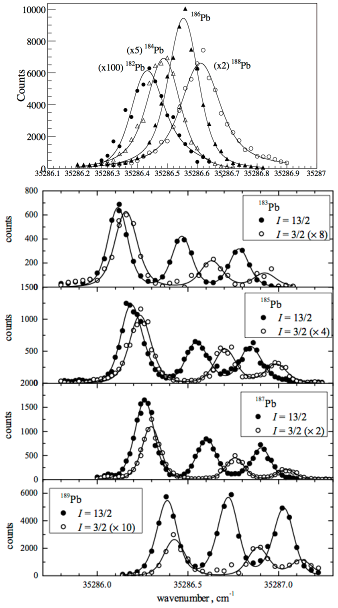
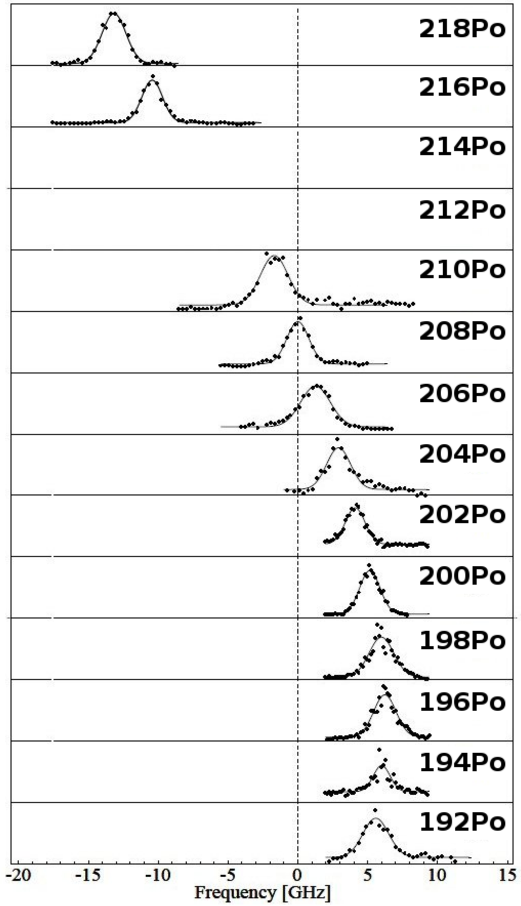
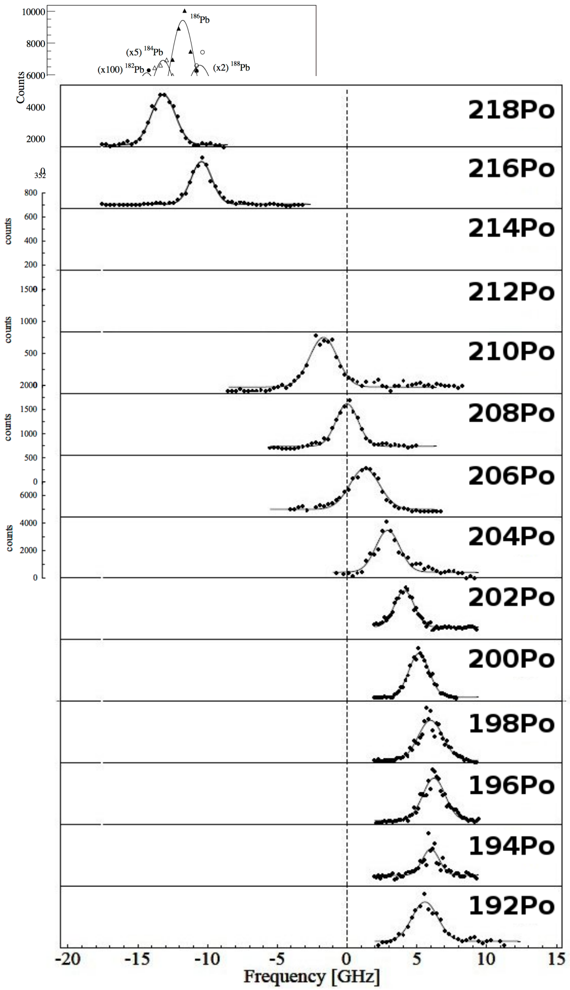
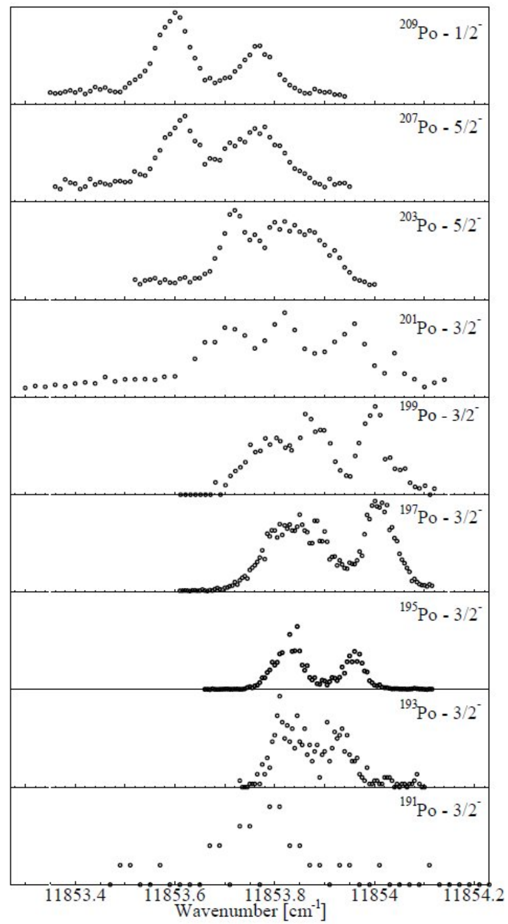


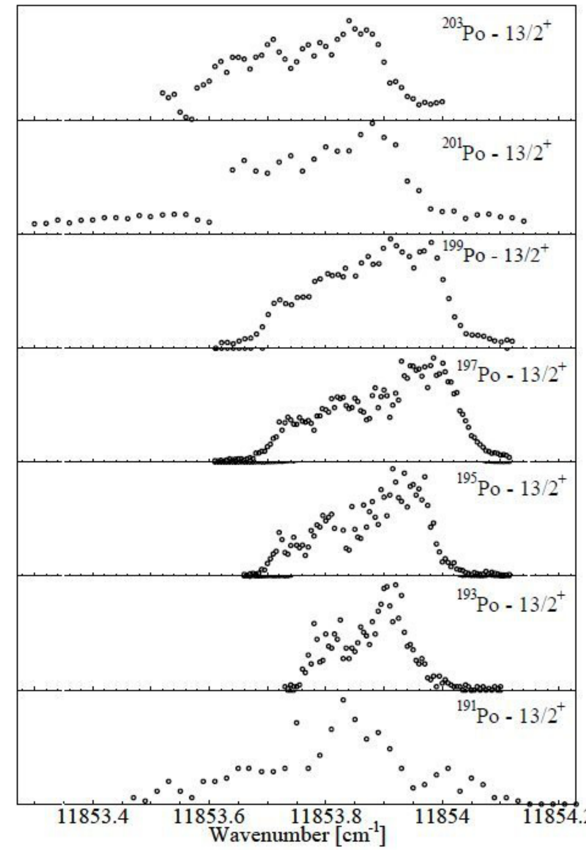


*Po: T.E. Cocolios et al., PRL **106**(2011)052503.*

Rich data collection!

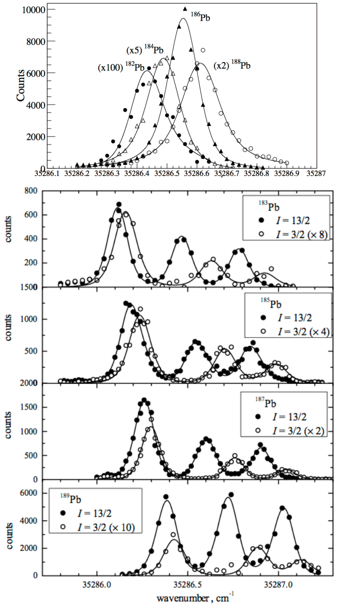


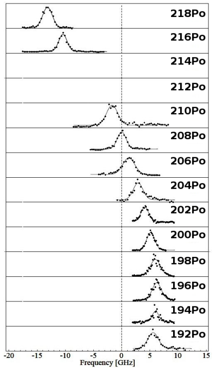


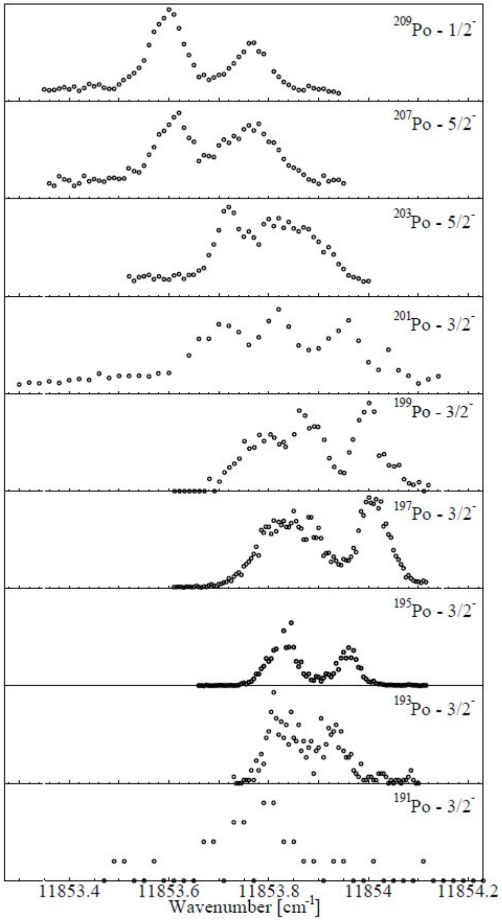


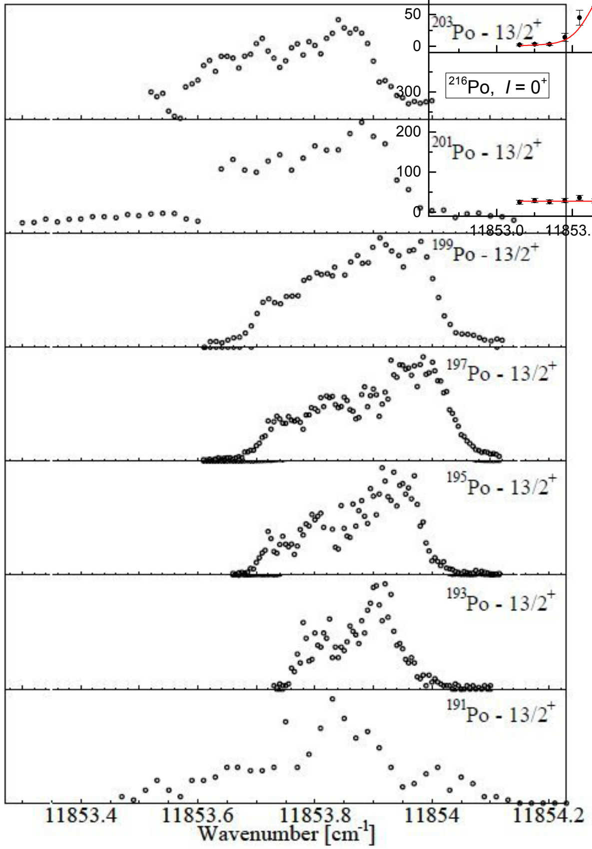
*Po: T.E. Cocolios et al., PRL **106**(2011)052503;*
*M.D. Seliverstov et al., PLB **719**(2013)362;*
*M.D. Seliverstov et al., PRC **89**(2014)034323.*

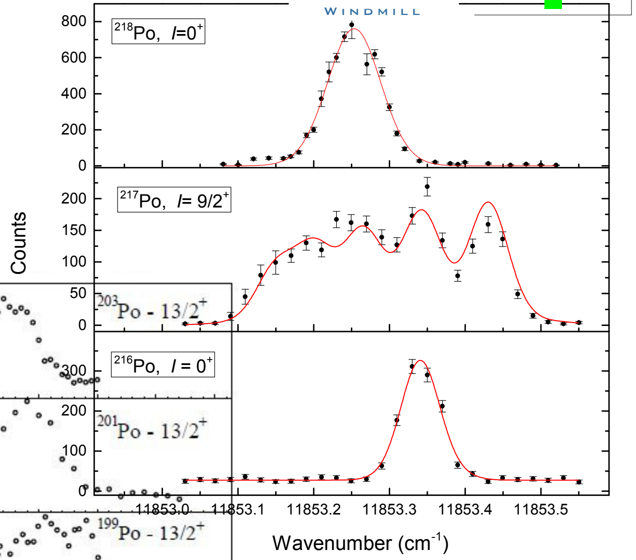
Rich data collection!





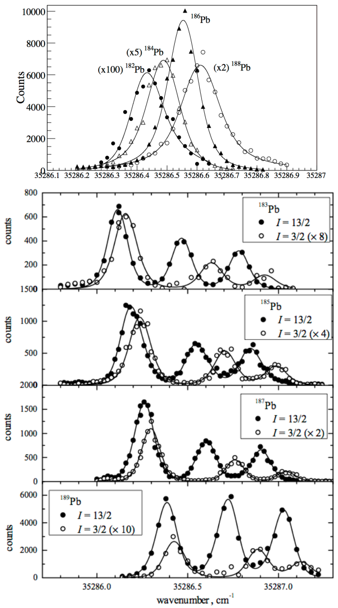


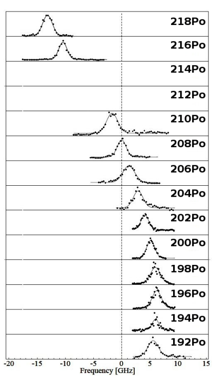


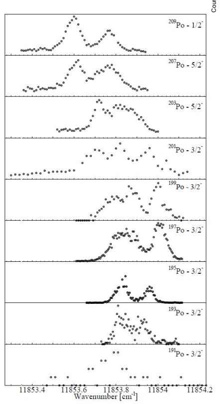


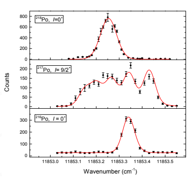
*Po: M.D. Seliverstov et al., PLB **719**(2013)362;*
*M.D. Seliverstov et al., PRC **89**(2014)034323;*
*D.A. Fink et al, PRX **5**(2015)011018.*

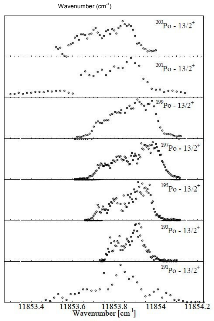
Rich data collection!

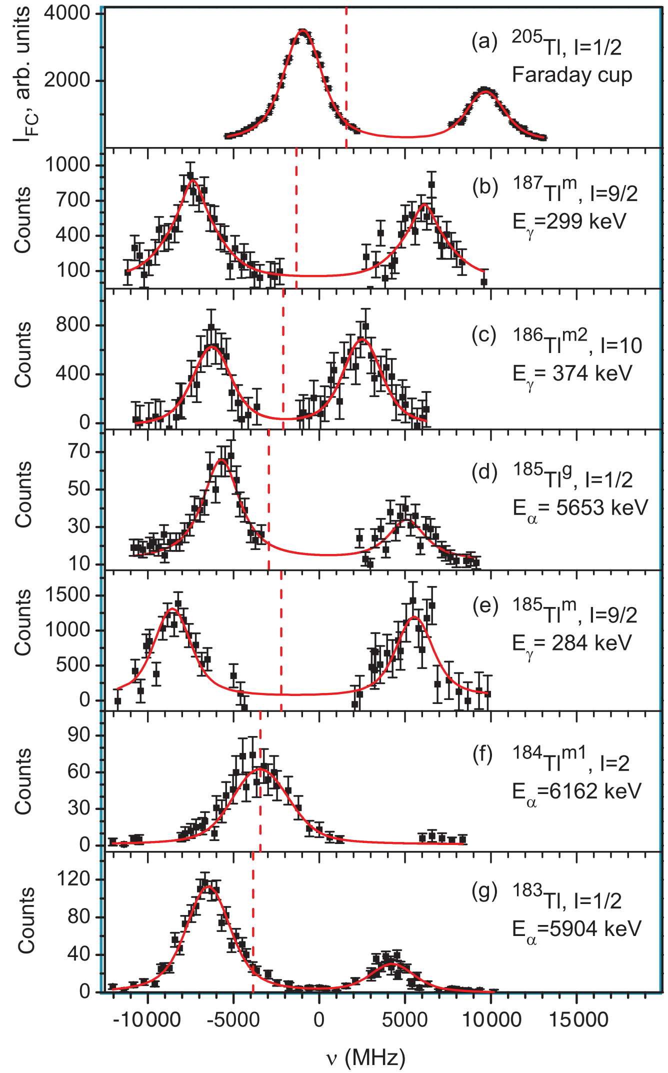












*Tl: A.E. Barzakh et al., PRC **86**(2012)014311;*
*A.E. Barzakh et al, .PRC **88**(2013)024315.*

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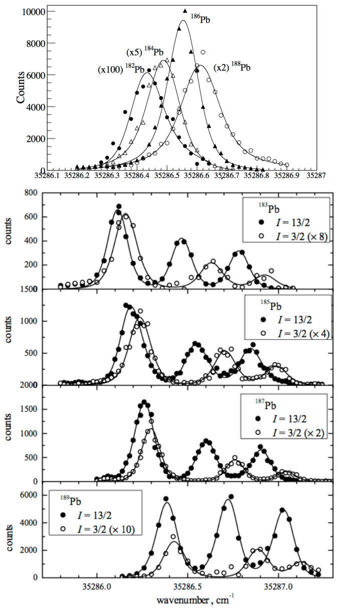
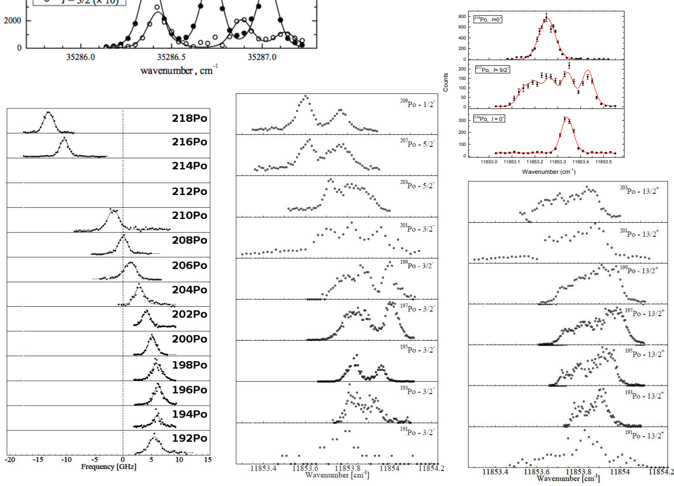
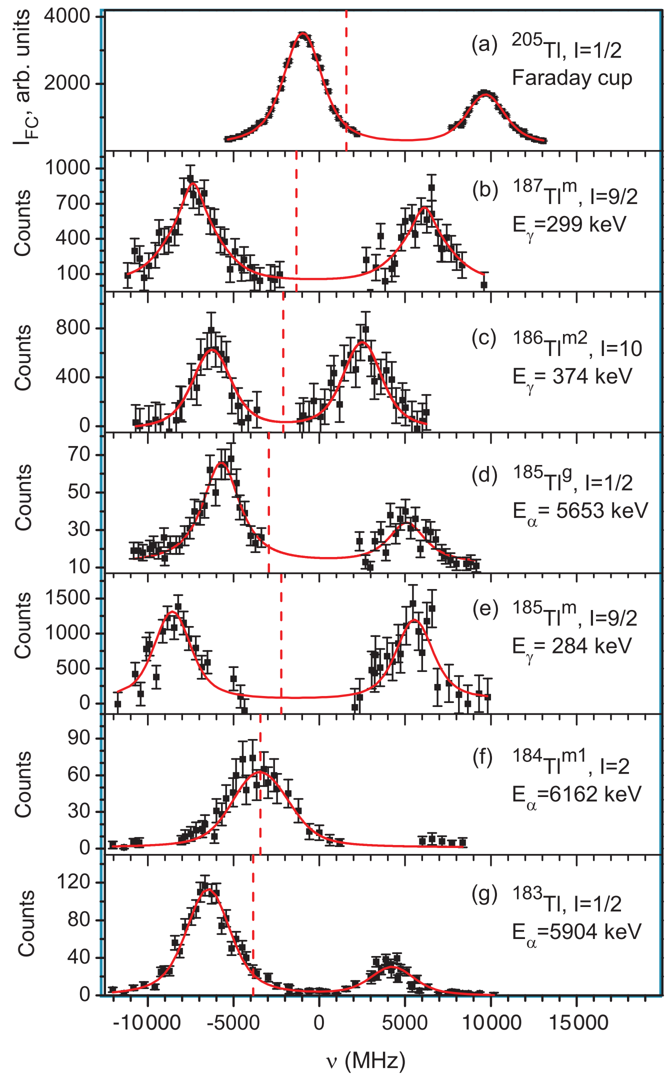
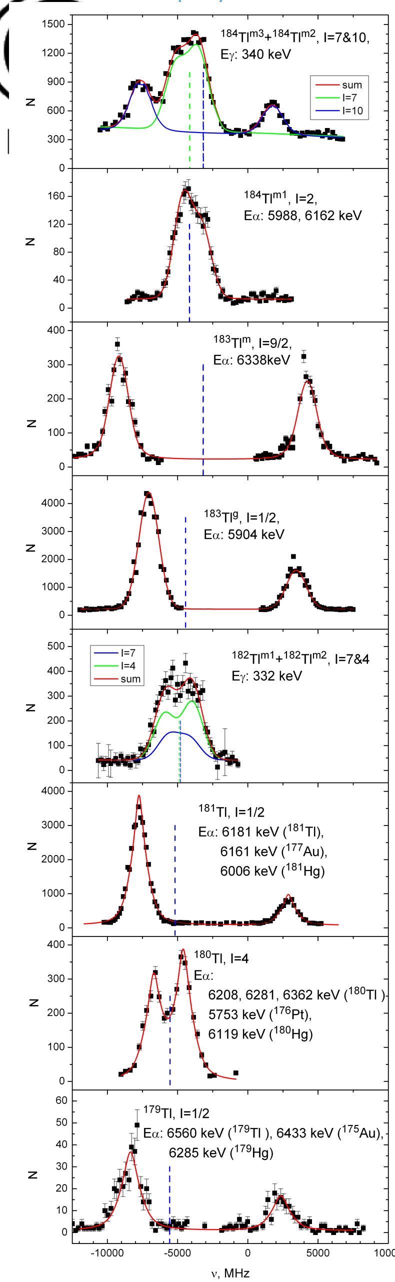


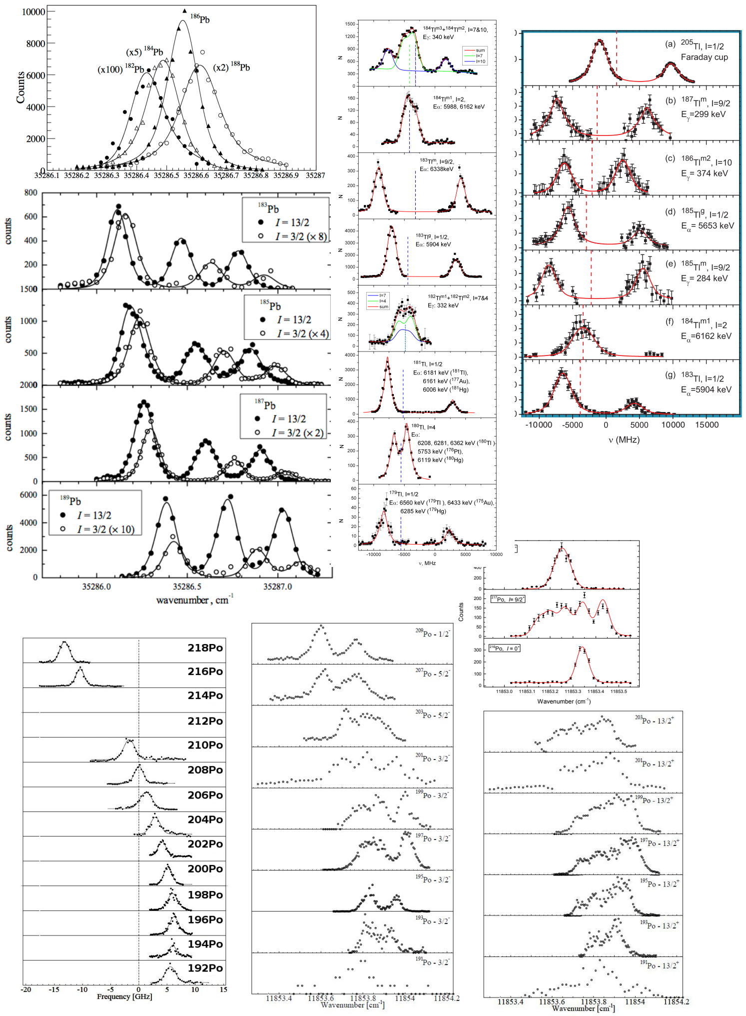






*Tl: A.E. Barzakh et al., PRC **86**(2012)014311;*
*A.E. Barzakh et al, .PRC **88**(2013)024315;*
C. Van Beveren, PhD Thesis KU Leuven (2016).

Rich data collection!



- ✦ $_{79}$Au
- ✦ $_{80}$Hg
- ▸ $_{81}$Tl
- ▸ $_{82}$Pb
- ✦ $_{83}$Bi
- ▸ $_{84}$Po
- ✦ $_{85}$At
- ✦ $_{89}$Ac

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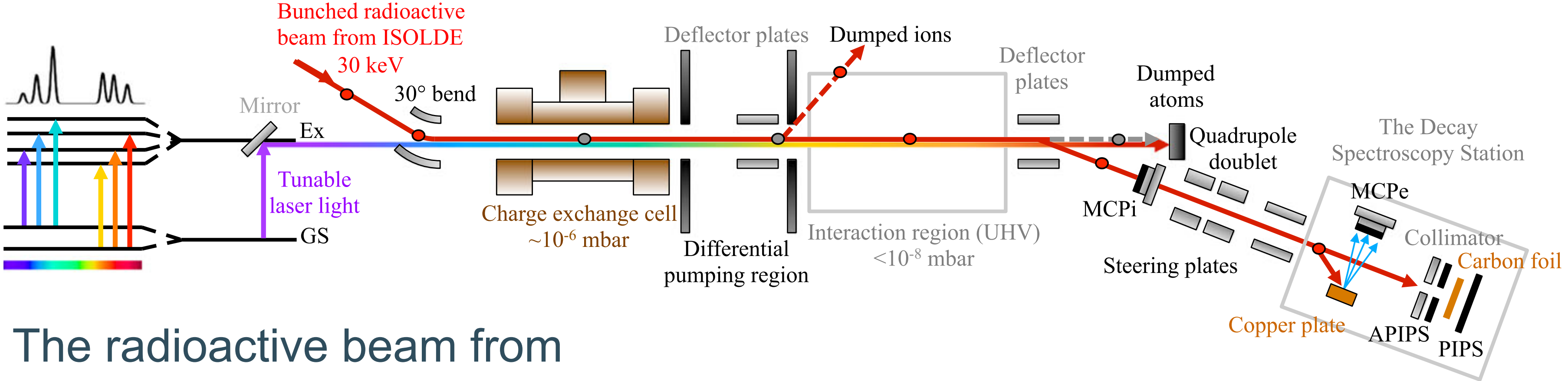
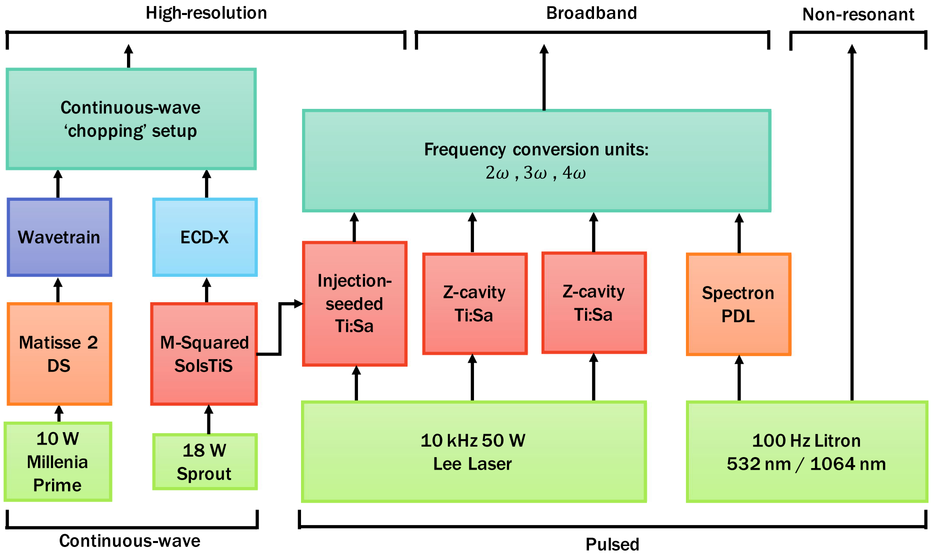
Collinear Resonance Ionization Spectroscopy



- The radioactive beam from ISOLDE is bunched and sent to the experiment;
- The ion bunch is neutralised;
- The atom bunch is irradiated by a sequence of laser pulses;
- On resonance, the atoms are re-ionised and sent to a detector (MCP / decay station) for counting.



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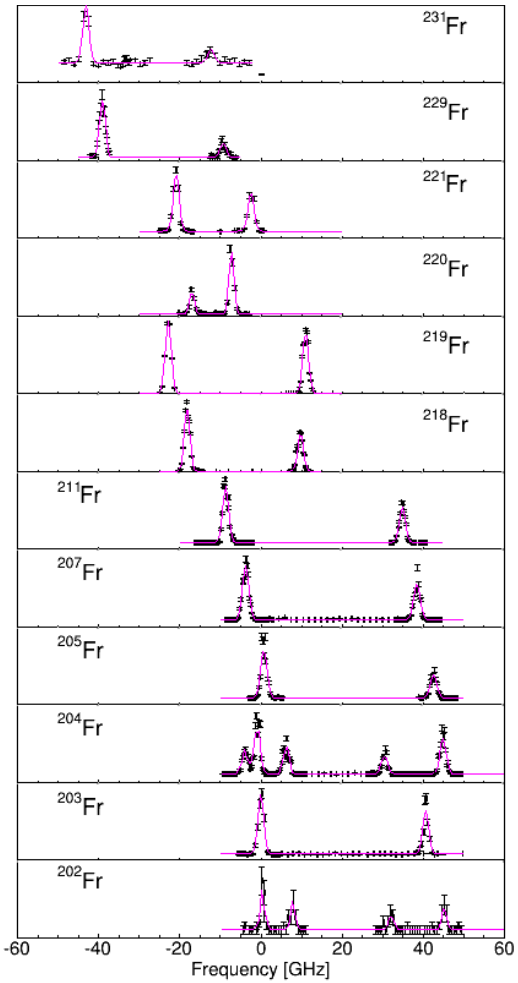
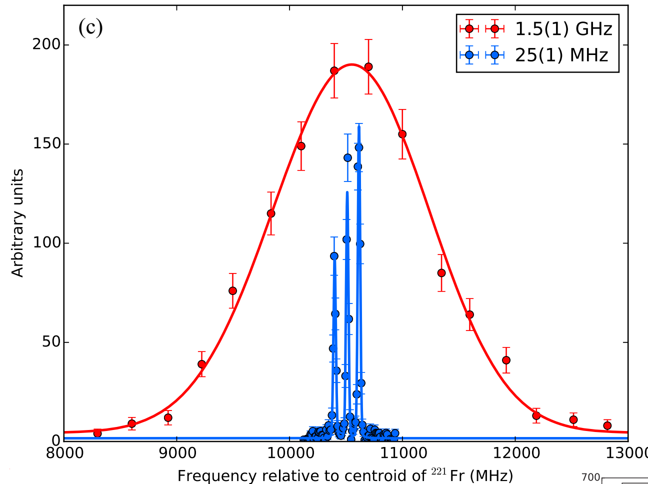
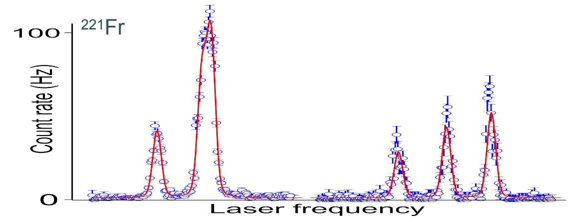
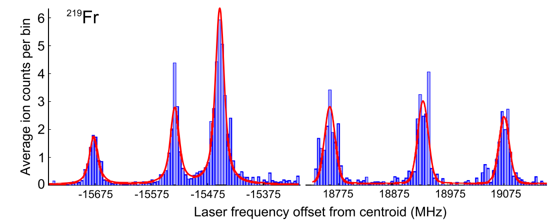
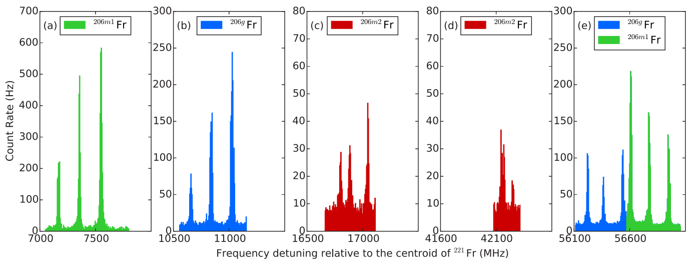
Bridging resolution and sensitivity

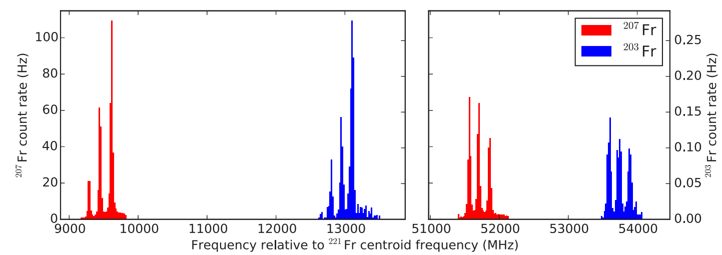












*Fr: K.T. Flanagan et al, PRL **111**(2013)212501;*
*R.P. de Groote et al, PRL **115**(2015)132501;*
*K.M. Lynch et al, PRC **93**(2016)014319;*
*S.G. Wilkins et al., PRC **96**(2017)034317.*

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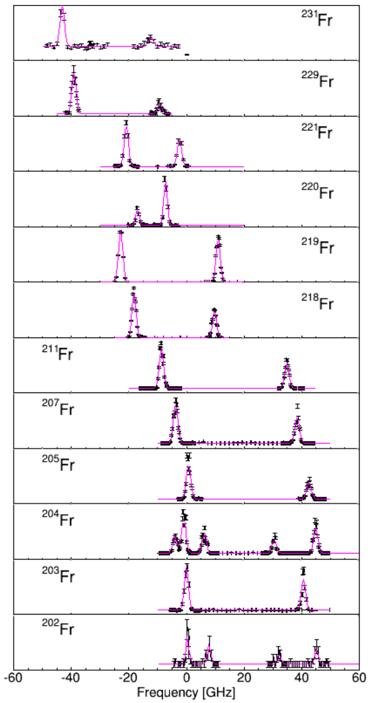
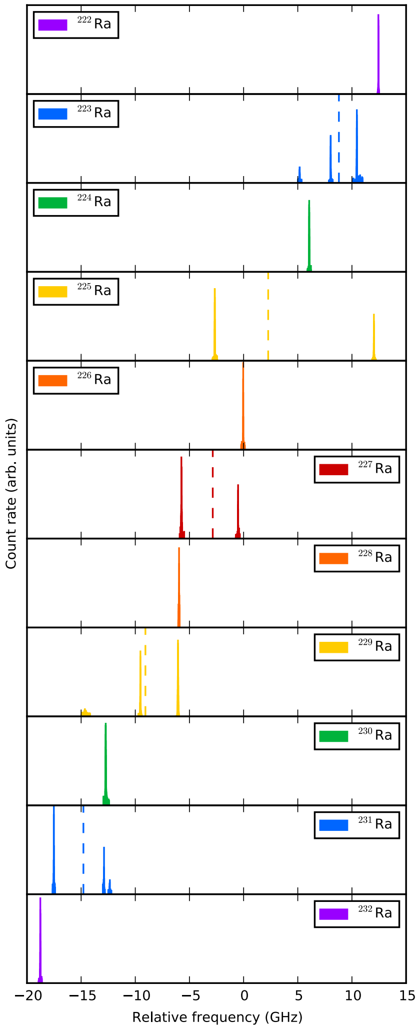
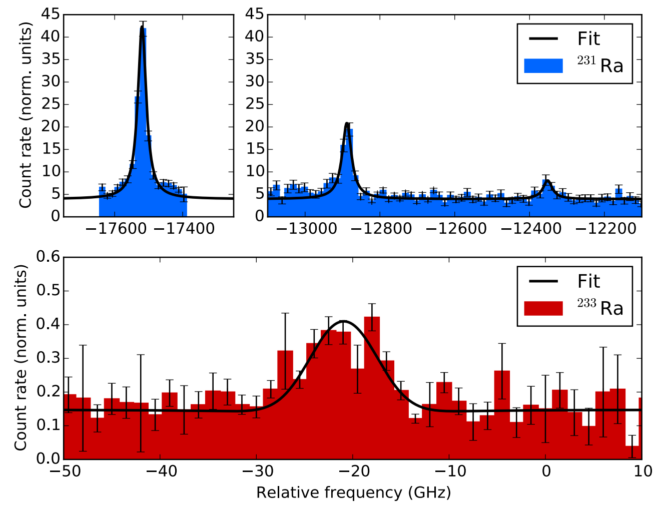
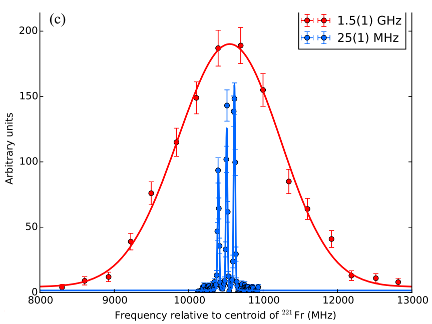
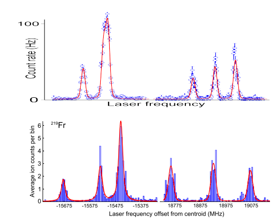
Bridging resolution and sensitivity

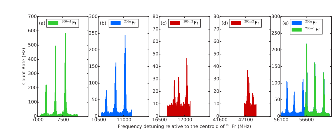


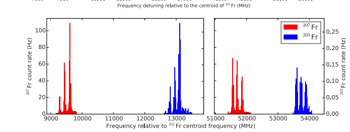












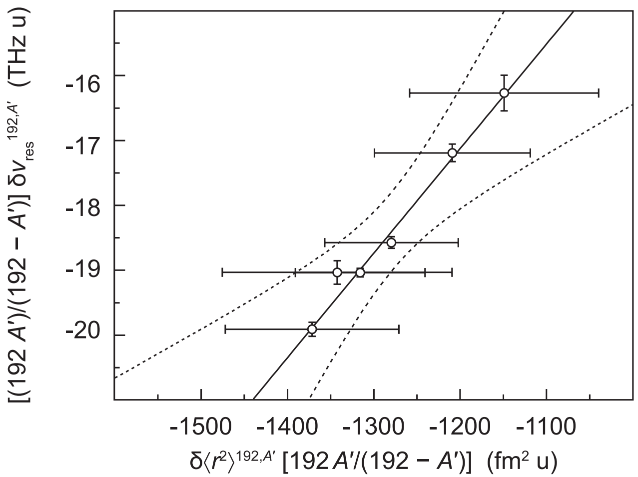
Ra: K.M. Lynch et al, submitted to PRC.

From isotope shift to charge radii

$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

The atomic parameters are essential to extract ∂<r²>
Given 3 independent <r²> measurements,
one may extract these experimentally…

$$\mu_{AA'}\delta\nu^{AA'} = M + F\mu_{AA'}\delta\langle r^2\rangle^{AA'}$$



$$\mu_{AA'} = \frac{AA'}{A'-A}$$

*Os: A. Kellerbauer et al., PRA **84**(2011)062510.*

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From isotope shift to charge radii

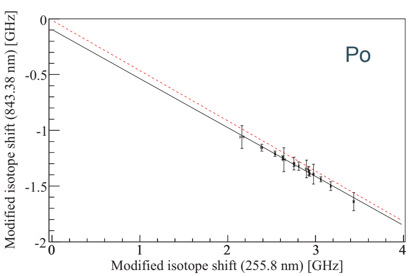
$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

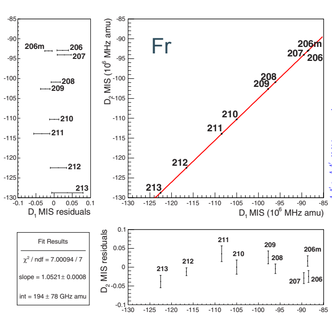
The atomic parameters are essential to extract ∂<r²>
In the absence of 3 independent <r²> measurements, one must rely on atomic calculations…

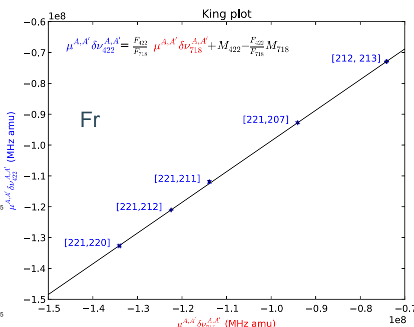
$$\mu_{AA'}\delta\nu_2^{AA'} = \frac{F_2}{F_1}\mu_{AA'}\delta\nu_1^{AA'} + \left(M_2 - \frac{F_2}{F_1}M_1\right)$$

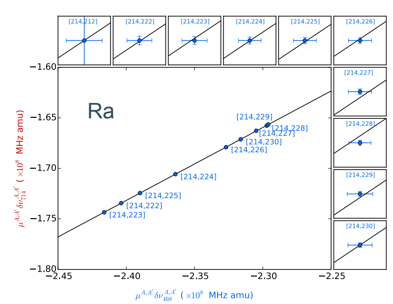
And compare multiple optical transitions:

$$\mu_{AA'} = \frac{AA'}{A'-A}$$









*King plots: T.E. Cocolios et al., PRL **106**(2011)052503;*
*B. Cheal, T.E. Cocolios & S. Fritzsche, PRA **86**(2012)042501;*
*K.M. Lynch et al, PRX **4**(2014)011055;*
*R. Collister et al., PRA **90**(2014)052502.*

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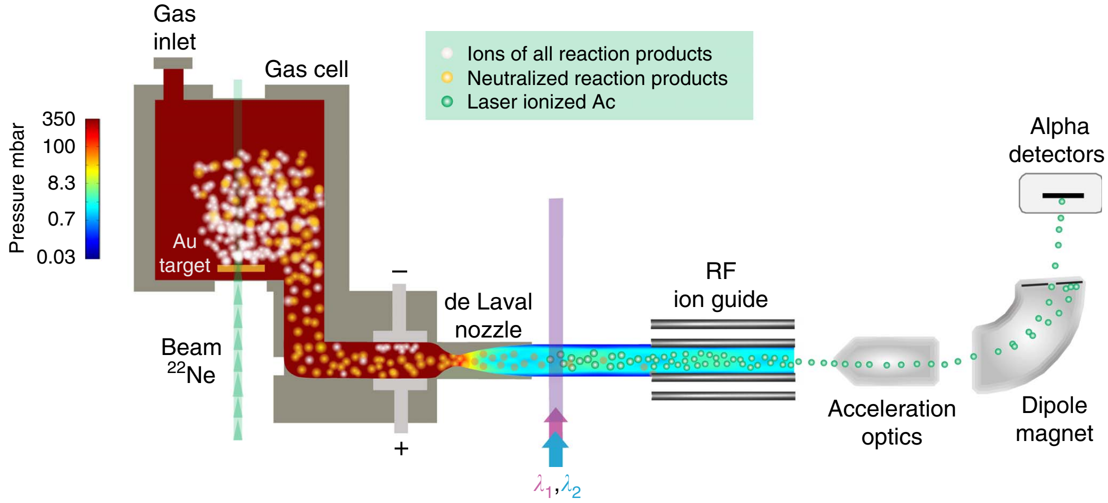
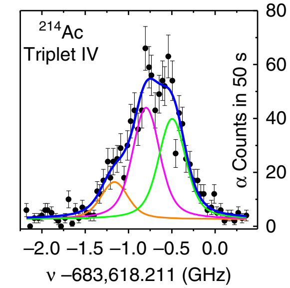
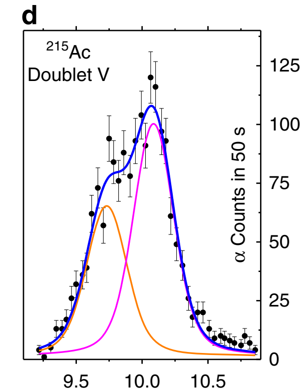
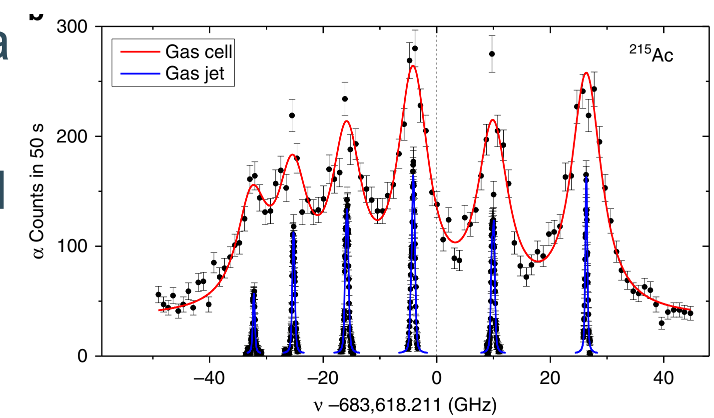
In-gas-jet laser spectroscopy







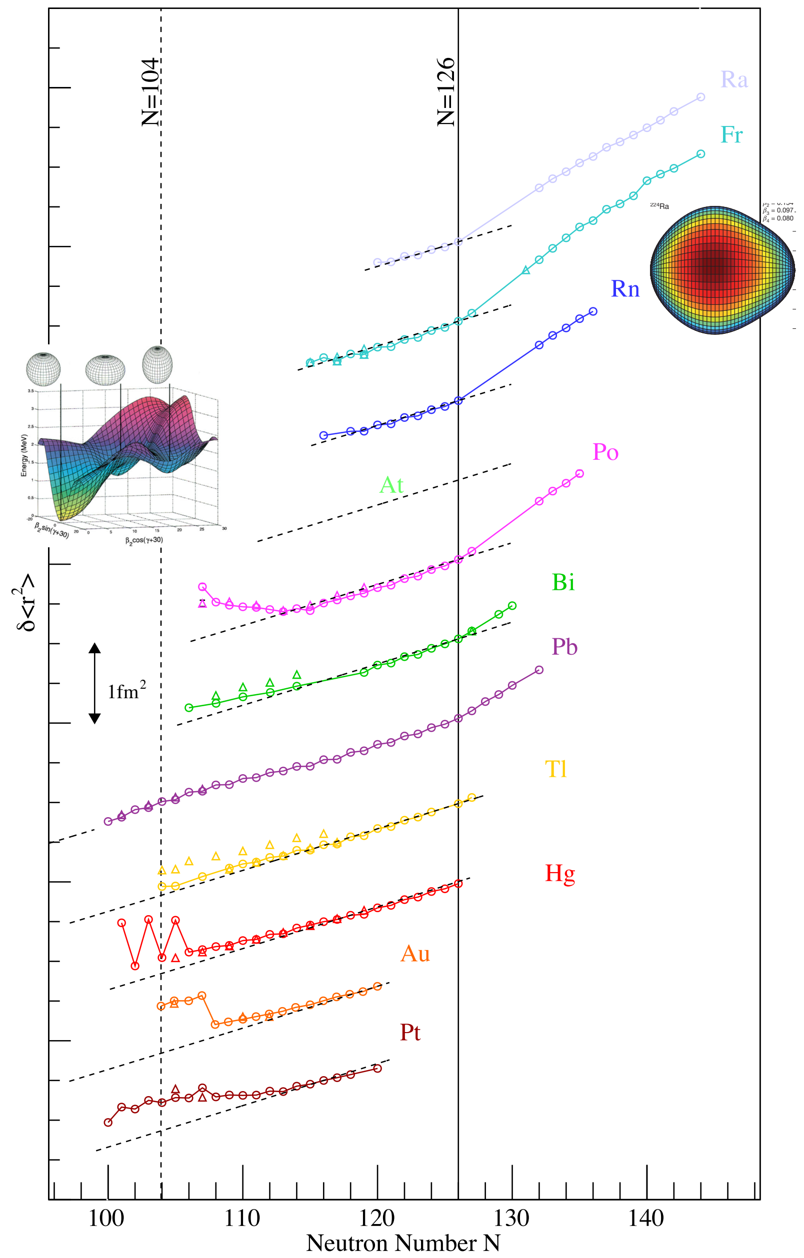


- The beam is produced off a thin target and the recoils are collected and neutralised in a noble;
- The atoms are guided towards a nozzle and laser beams are shown either in the exit channel (in-gas) or in the (super-)sonic jet;
- The experiment is performed just as others.

*Ac: R. Ferrer et al, Nature Comm. **8**(2017)14520.*

∂<r²> around Z~82

- Rich physics can be extracted from these systematic isotopic chains;
- Comparison to the spherical droplet model gives an indication of the departure from sphericity (Ir, Pt, Au, Hg, ^{m}Tl, Bi, Po, At);
- Kink at N=126 is characteristic of a major shell closure, though the origin of it magnitude remains an open debate;
- Odd-even staggering reversal in the neutron-rich isotopes is found where those isotopes also display octupole deformation.



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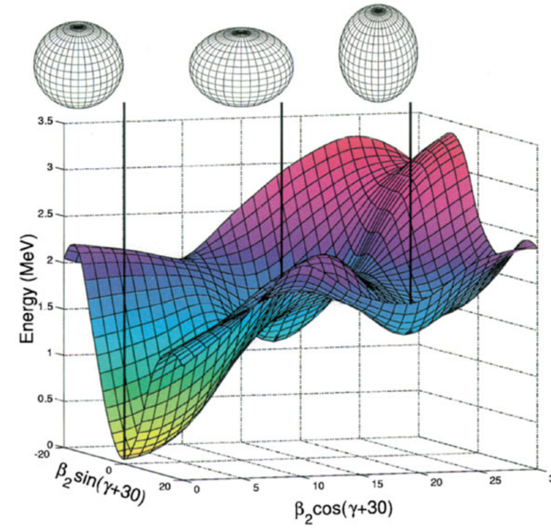
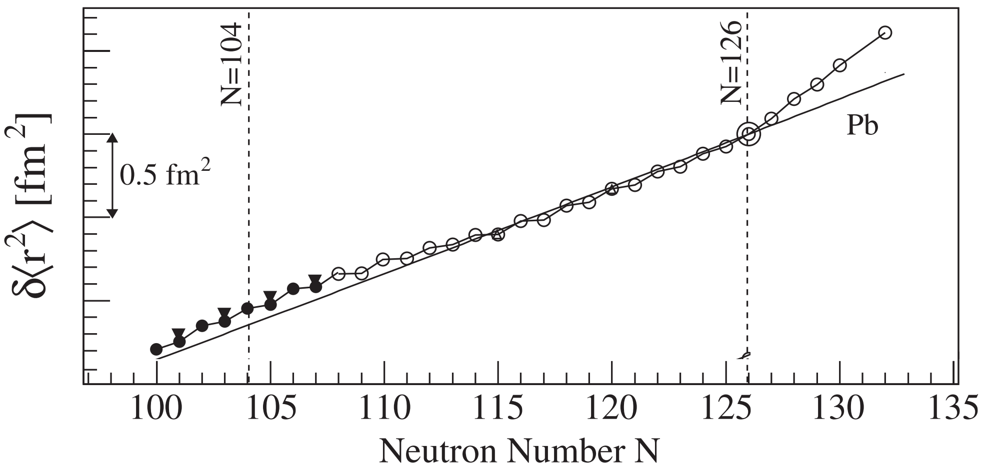
Pb: the baseline



- In spite of the triple shape coexistence found in ^{186}Pb and the general proximity of all shapes near N=104, there is no evidence of a departure from sphericity in the Pb ground-state or isomer charge distribution.
- This trend is well reproduced by Beyond Mean Field calculations and IBM calculations.



*Pb: H. De Witte et al., PRL **98**(2007)112502.*

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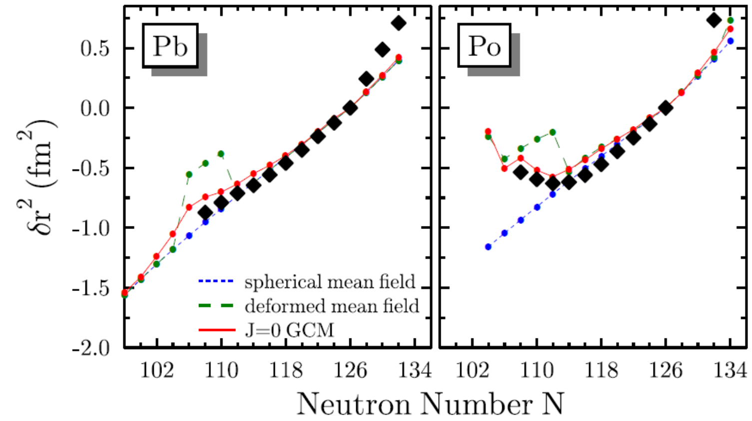
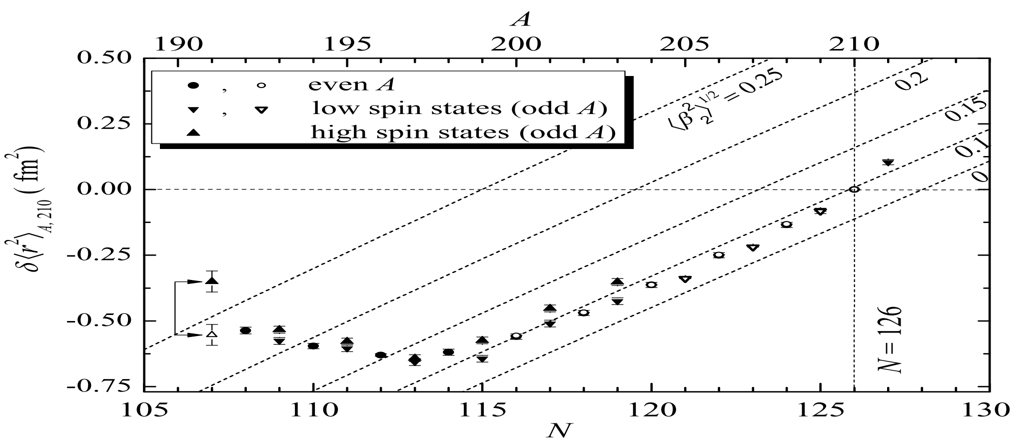
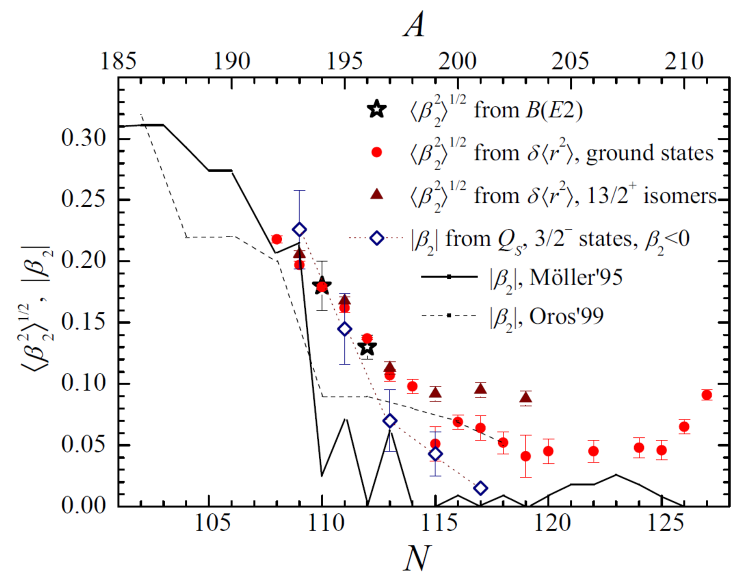
Po: the smooth departure

- Smooth onset of deformation is found from N=116 downwards.
- BMF calculations reproduce the trend very well and claim no intrinsic deformation.
- Comparison of β_2 between $\partial\langle r^2\rangle$, Q_S, and B(E2) suggests the deformation is static.







*BMF: T. Grahn et al., PRL **97**(2006)062501;*
*T. Grahn et al, NPA **801**(2008)83.*

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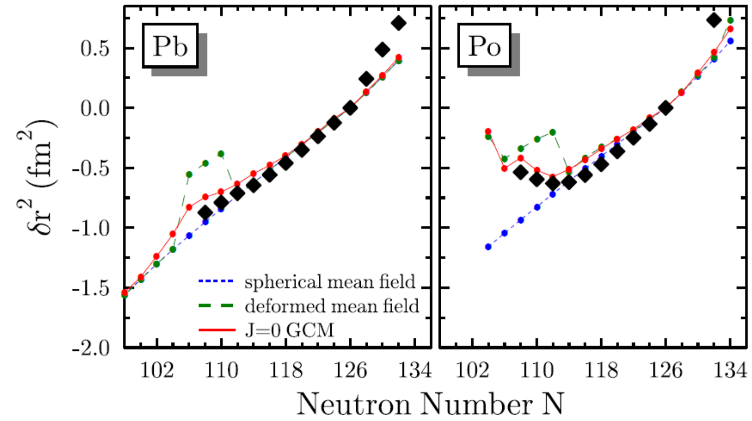
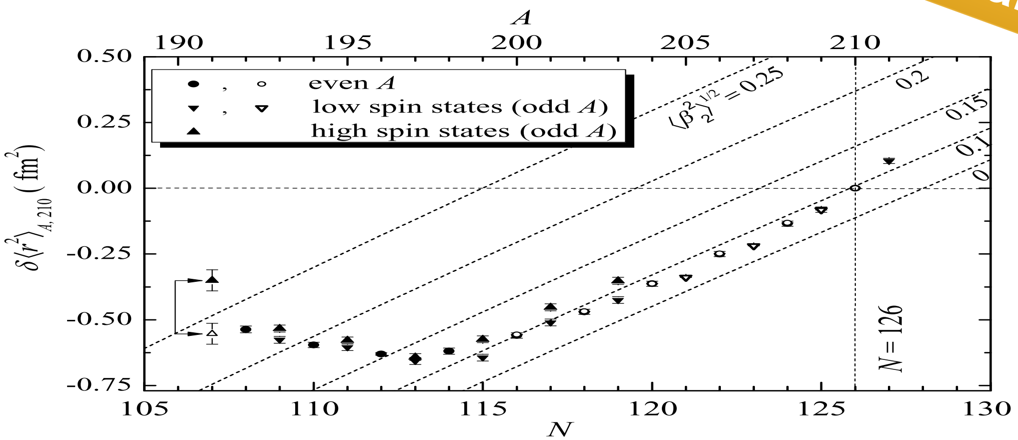
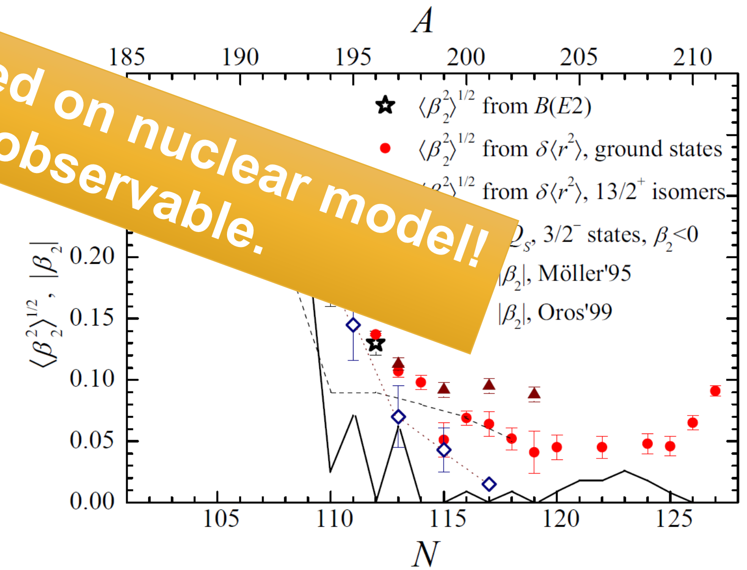


β_2 extraction is based on nuclear model!
It is NOT an observable.





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Extracting β2

Quadrupole moment

$$Q_s = Q_0 \left(\frac{3\Omega^2 - I(I+1)}{(I+1)(2I+3)} \right)$$

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

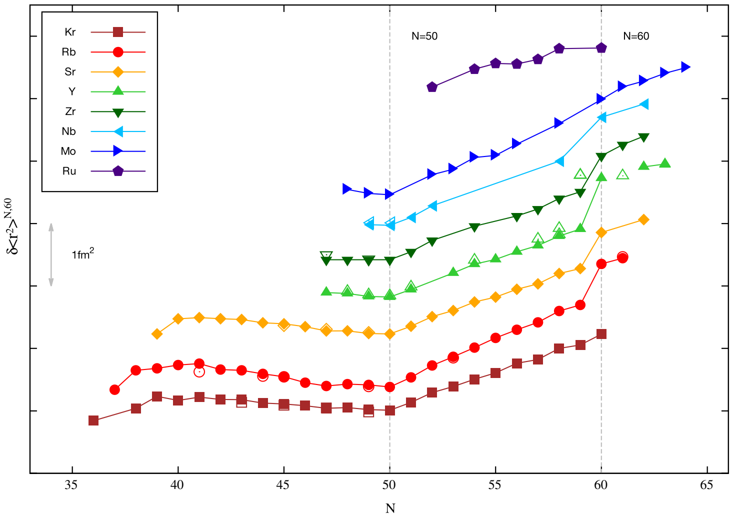
Charge distribution

$$\langle r^2 \rangle = \langle r^2 \rangle_{\text{sph}} \left(1 + \frac{5}{4\pi} \sum_{i=2}^{\infty} \langle \beta_i^2 \rangle \right) + 3\sigma^2$$

$$\delta \langle r^2 \rangle^{A,A'} = \delta \langle r^2 \rangle_{\text{sph}}^{A,A'} + \langle r^2 \rangle_{\text{sph}} \frac{5}{4\pi} \sum_{i=2}^{\infty} \delta \langle \beta_i^2 \rangle^{A,A'}$$

Coulomb excitation

$$\langle \beta_\lambda^2 \rangle = \left(\frac{4\pi}{3ZeR_0^\lambda} \right)^2 \sum_f B(E\lambda : J_{\text{gs}} \to J_f)$$

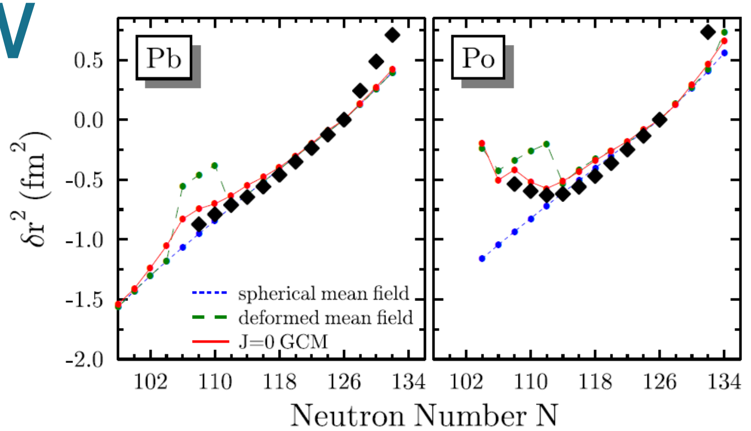


$$\langle \beta_2^2 \rangle = \langle \beta_2 \rangle^2 + \left(\langle \beta_2^2 \rangle - \langle \beta_2 \rangle^2 \right) = \beta_{\text{static}}^2 + \beta_{\text{dynamic}}^2$$

- This approach has been successfully used in the Y isotopes to show that there is a stepwise change in shape at N~60.

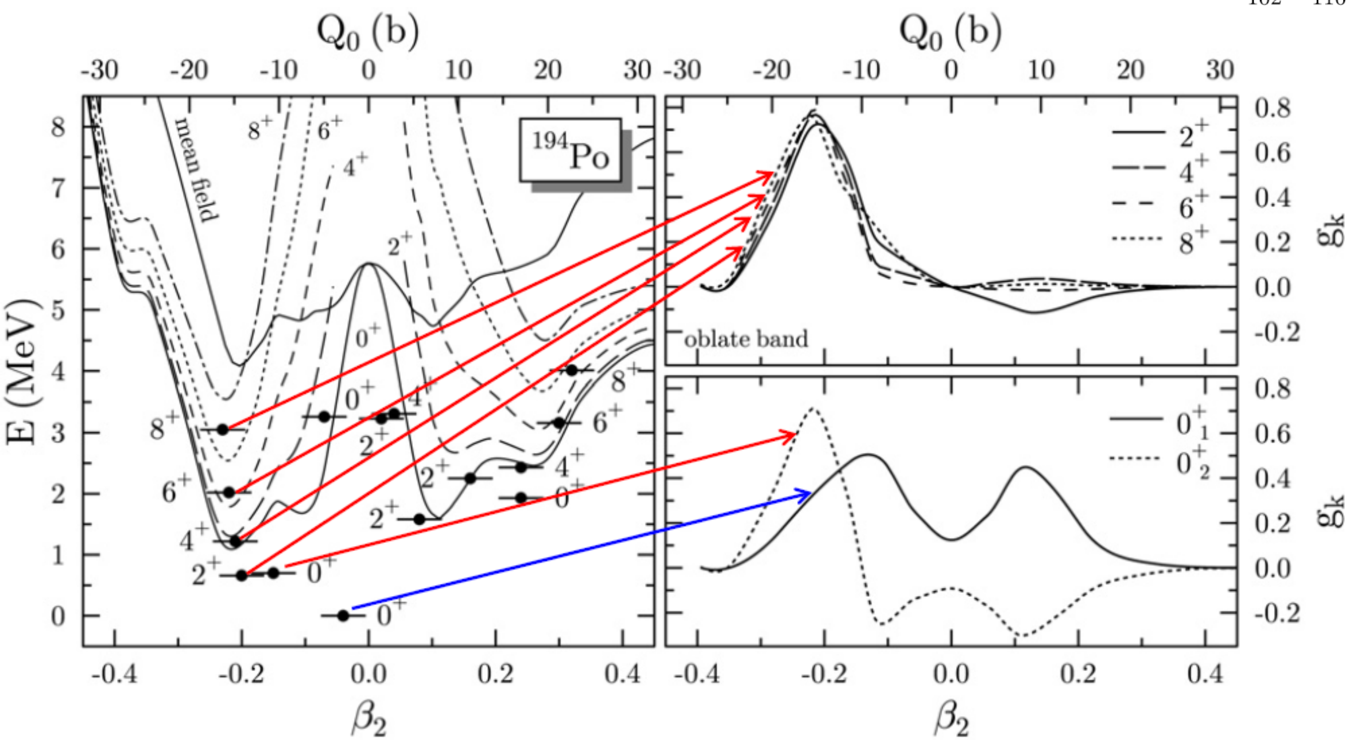
*Laser spec.: B. Cheat & K.T. Flanagan, JPG **37**(2010)113101; P. Campbell, I.D. Moore & M.R. Pearson, PPNP **86**(2016)127.*

Back to Po: BMF view



Ground state only

All states



*BMF: T. Grahn et al., PRL **97**(2006)062501;*
*T. Grahn et al, NPA **801**(2008)83.*

Laser spectroscopy & shapes

- Extensive data has been gathered in the Z~82 region in the last decade.
- Beyond the original observation of shape staggering in Hg, a lot of new evidence of shape evolution has been gathered
  - ➡ Sphericity in Pb
  - ➡ Smooth onset of deformation in Po & At
  - ➡ Return to sphericity in Au & Hg? => under investigation
  - ➡ Large isomer shift in Ir, Tl, Bi => shape coexistence

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  - ➡ Large isomer shift in Ir, Tl, Bi => shape coexistence
- Furthering mapping of the edges of this region
  - ➡ New data on Au, Hg, Tl, Bi, At to be published in the coming months
  - ➡ Southward: study of Os, W, … (out of reach of thick-target ISOL)
  - ➡ Northward: Rn, Fr, Ra, … (out of reach of current techniques)
- Moving on to a new domain => actinides & super heavies

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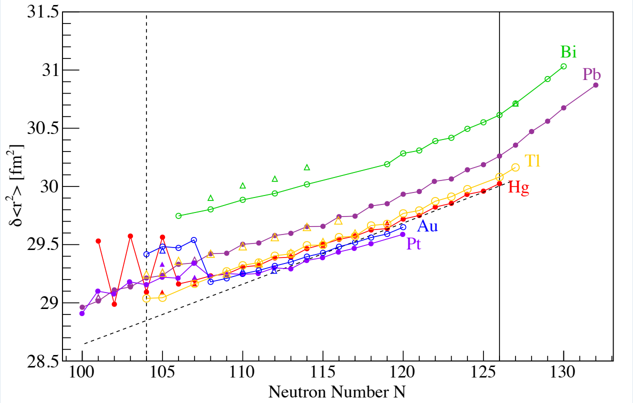

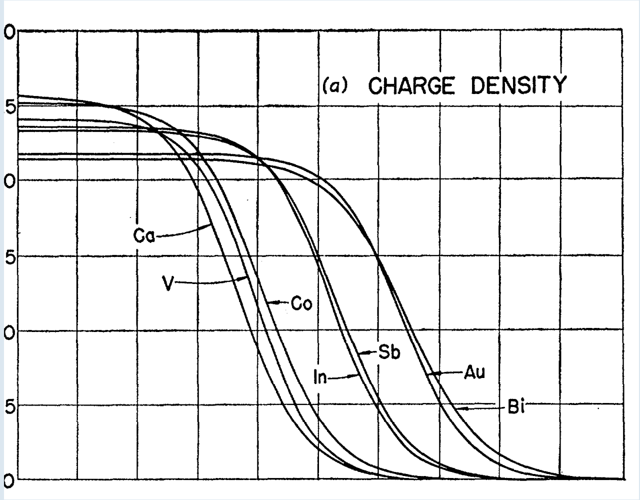

Absolute charge radii

A different perspective on the same data

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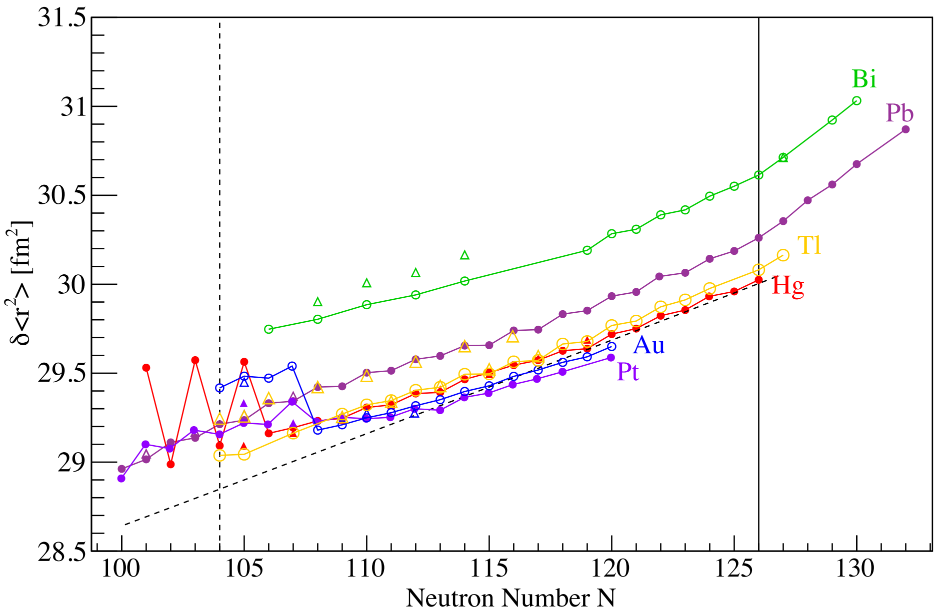
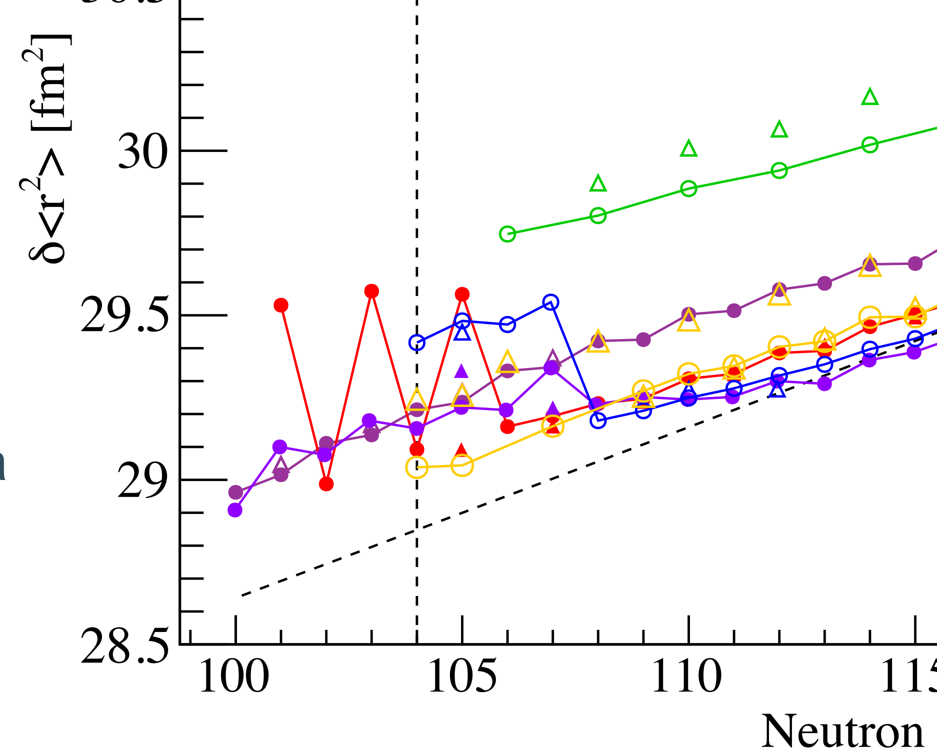
Absolute charge radii

- The available data are limited as there are no anchor point beyond $_{83}$Bi.
- The picture is rather messy as everything seem to overlap near N=104.
- The systematic uncertainty is not fully propagated on this picture and can grow dramatic as the data get further from the reference isotope.



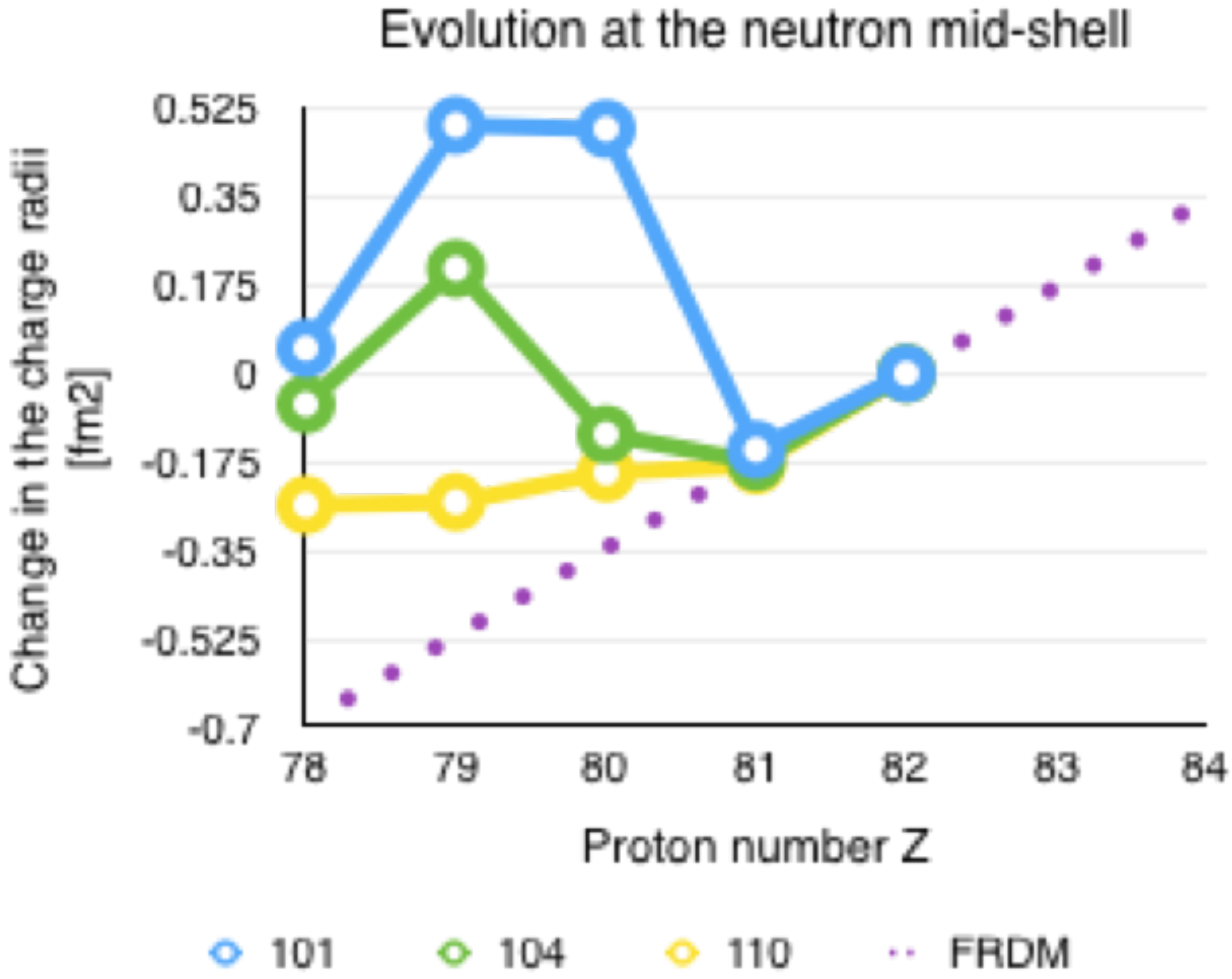
Shapes & sizes



- The jump between Pb & Bi is large as the Z=82 shell is crossed.
- The spread for Z<82 is irregular with a large jump from Tl to Hg, then a cluster until Pt, and finally a large jump to Ir again.
- Many unexpected features…
  - ^{m}Tl is a perfect match to Pb;
  - ^{g}Tl & Hg are a perfect match;
  - Deformed Pt match with Pb & ^{m}Tl;
  - Deformed Au & Hg do not match anything;
  - Extending data on Au, Hg, and Bi is essential.

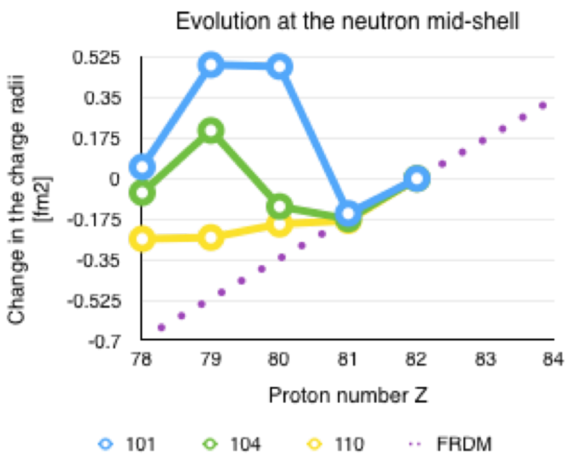
*T.E. Cocolios, Hyperfine Interactions **238**(2017)16.*

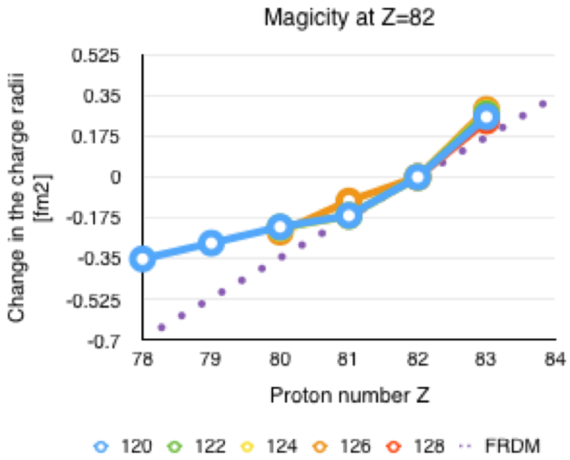
Isotonic evolution

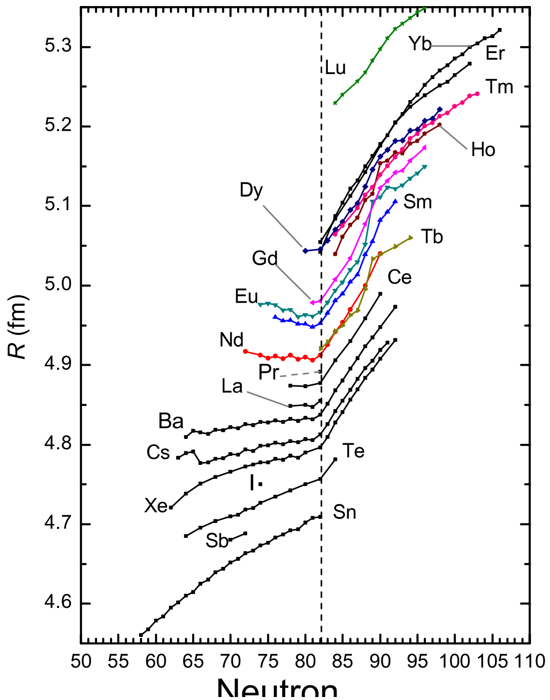


*T.E. Cocolios, Hyperfine Interactions **238**(2017)16.*

Isotonic evolution







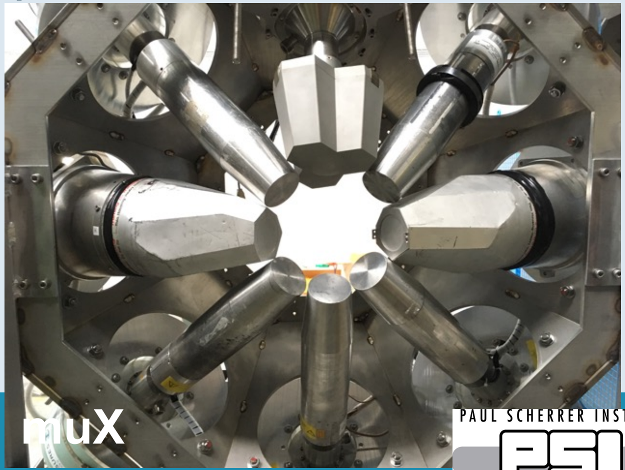
- Z~82 and N~82 display strikingly similar features:
  - Kink at the shell closure;
  - Similar behaviour between chains to first order;
  - Slight increase below the shell closure, e.g. in Eu. More data is required for N<82!

*N=82: I. Angeli & K.P. Marinova, ADNDT **99**(2013)69.*

Absolute radii & sizes

- The data on absolute radii is much more limited than that on relative radii.
- The impact of the propagation of the systematic uncertainties makes firm conclusions more difficult.
- The interpretation of the data is questionable. Are the various overlaps purely coincidental or do they carry more information than we have considered so far?

➡ We need new approaches to collect data on absolute $\langle r^2 \rangle$ on exotic nuclei using old techniques (muonic x-rays, electron scattering, …) on radioactive isotopes!



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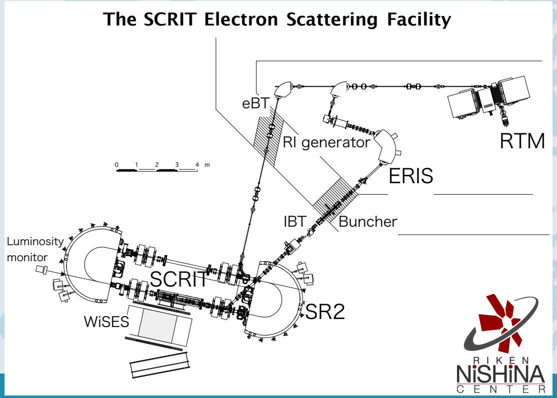

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Laser-assisted work

Using the lasers to help identify / purify the isotopes of interest…

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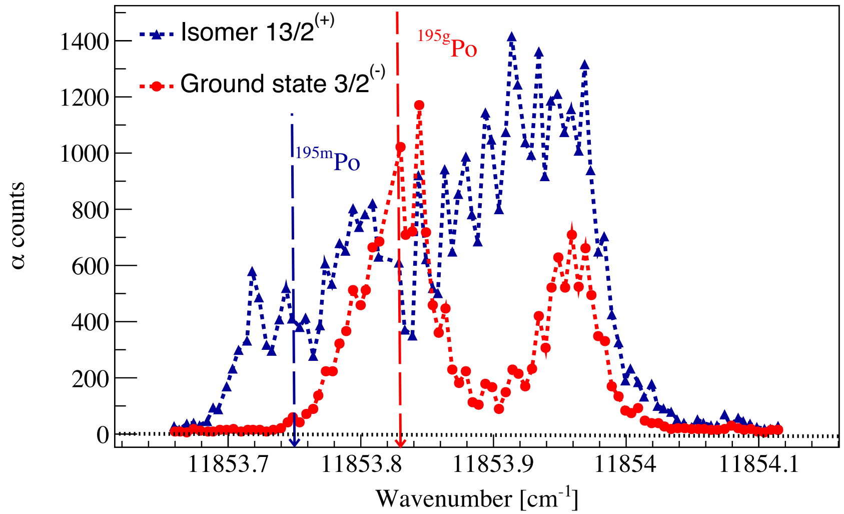
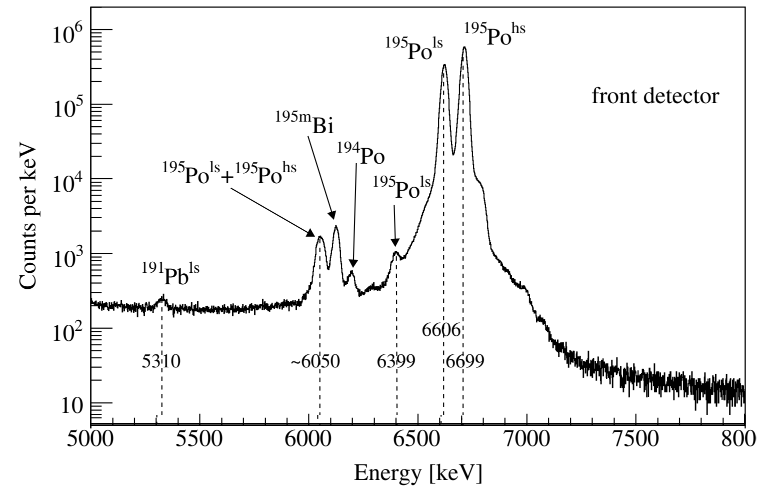
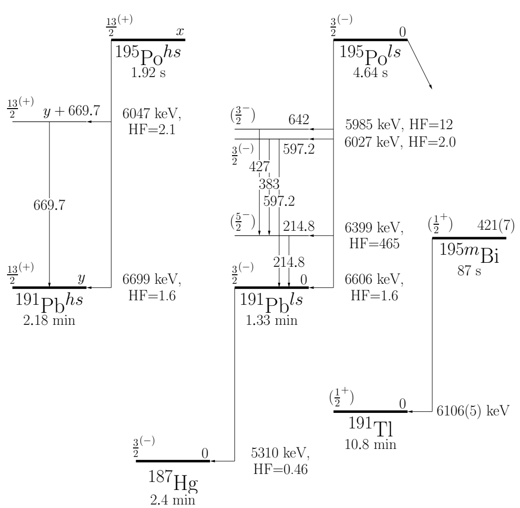
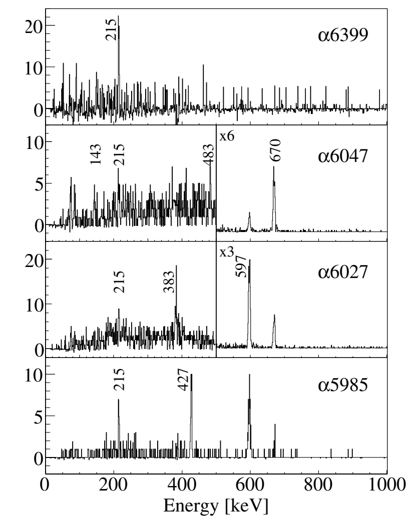
α-decay spectroscopy of ^{195}Po







- Isomer selection with RILIS using the different hyperfine structures;
- α-γ correlations revealed new details of the low-energy structure of ^{191}Pb.



^{195}Po decay: T.E. Cocolios et al., JPG **37**(2010)125103.

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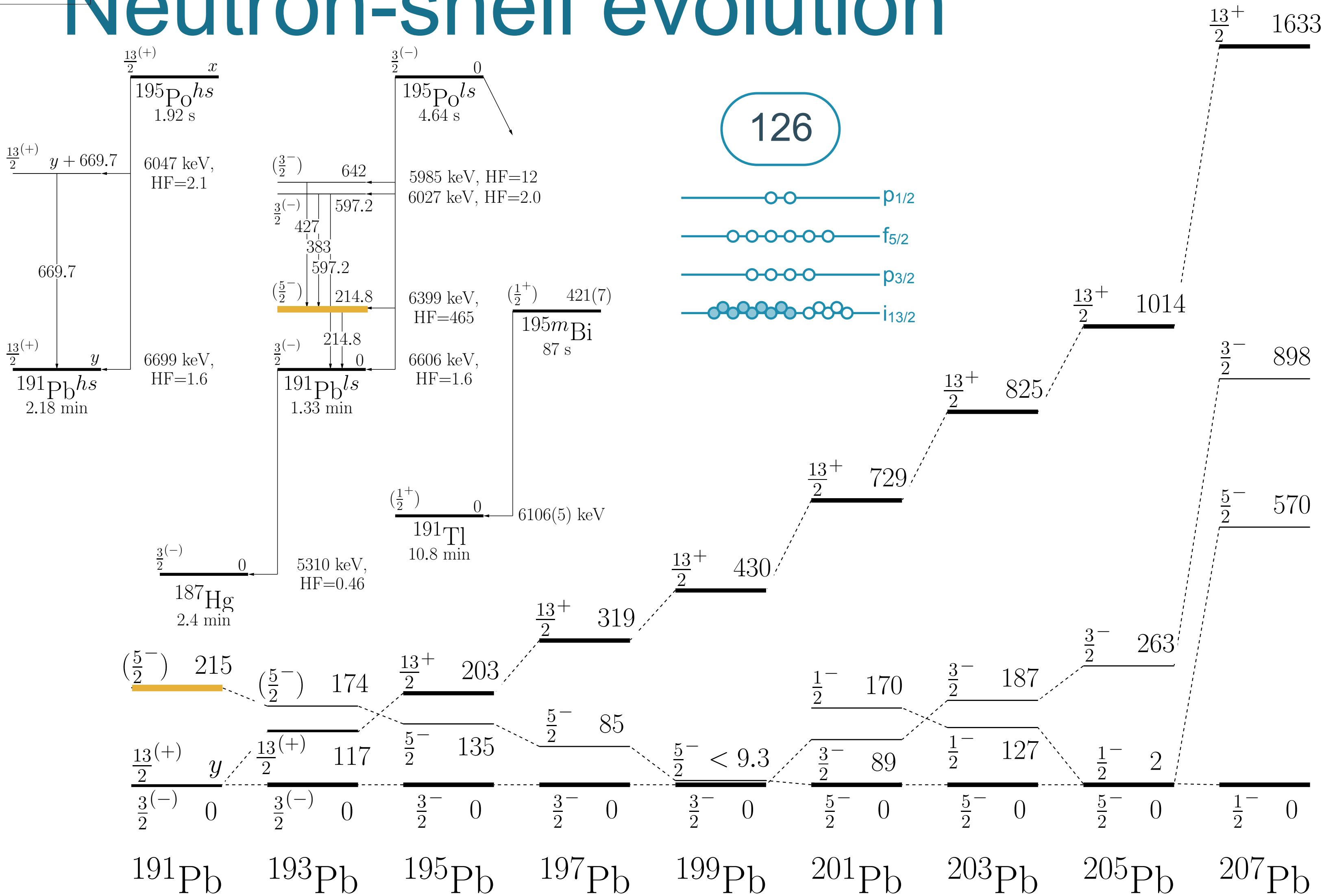
Neutron-shell evolution



^{195}Po decay: T.E. Cocolios et al., JPG **37**(2010)125103.

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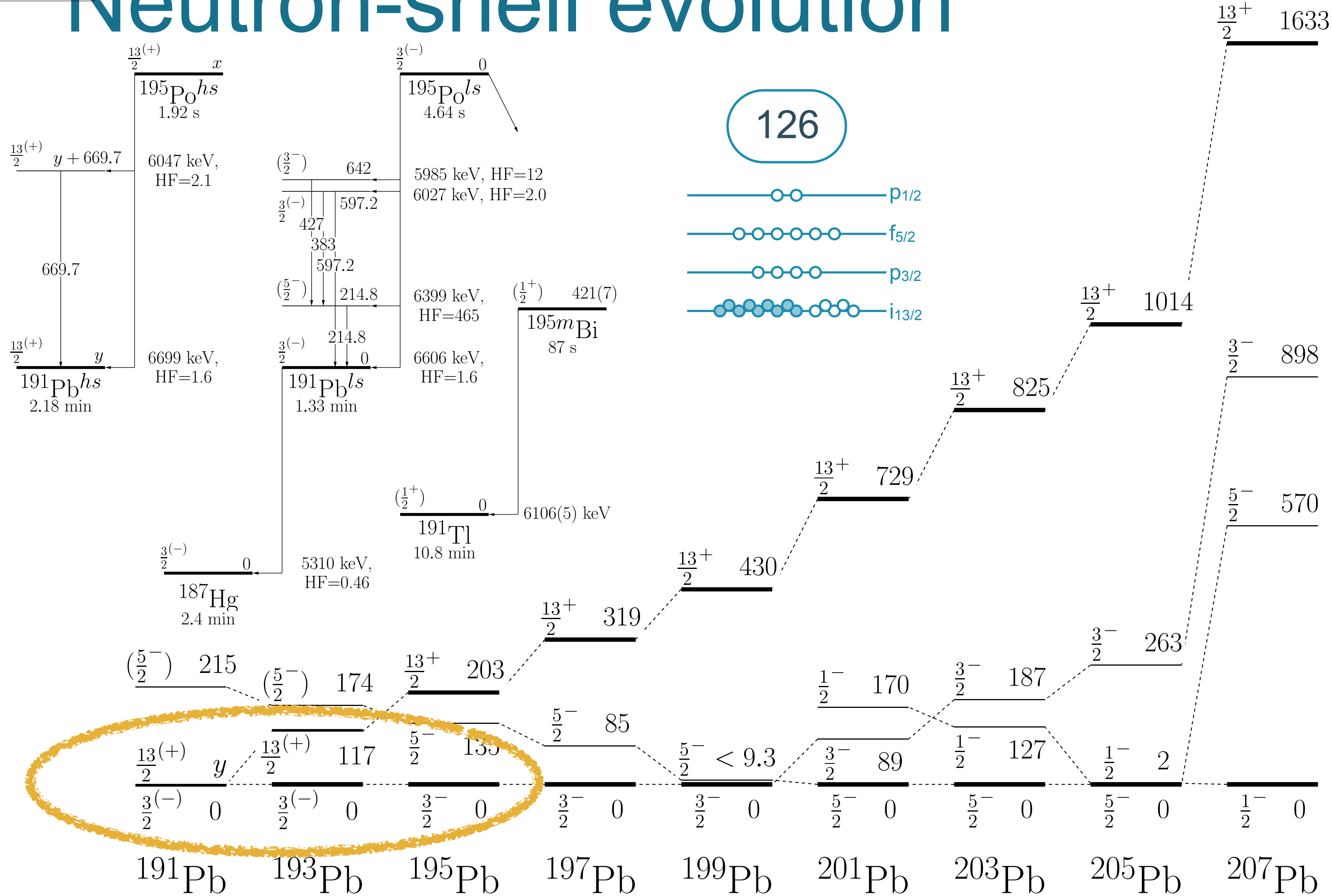
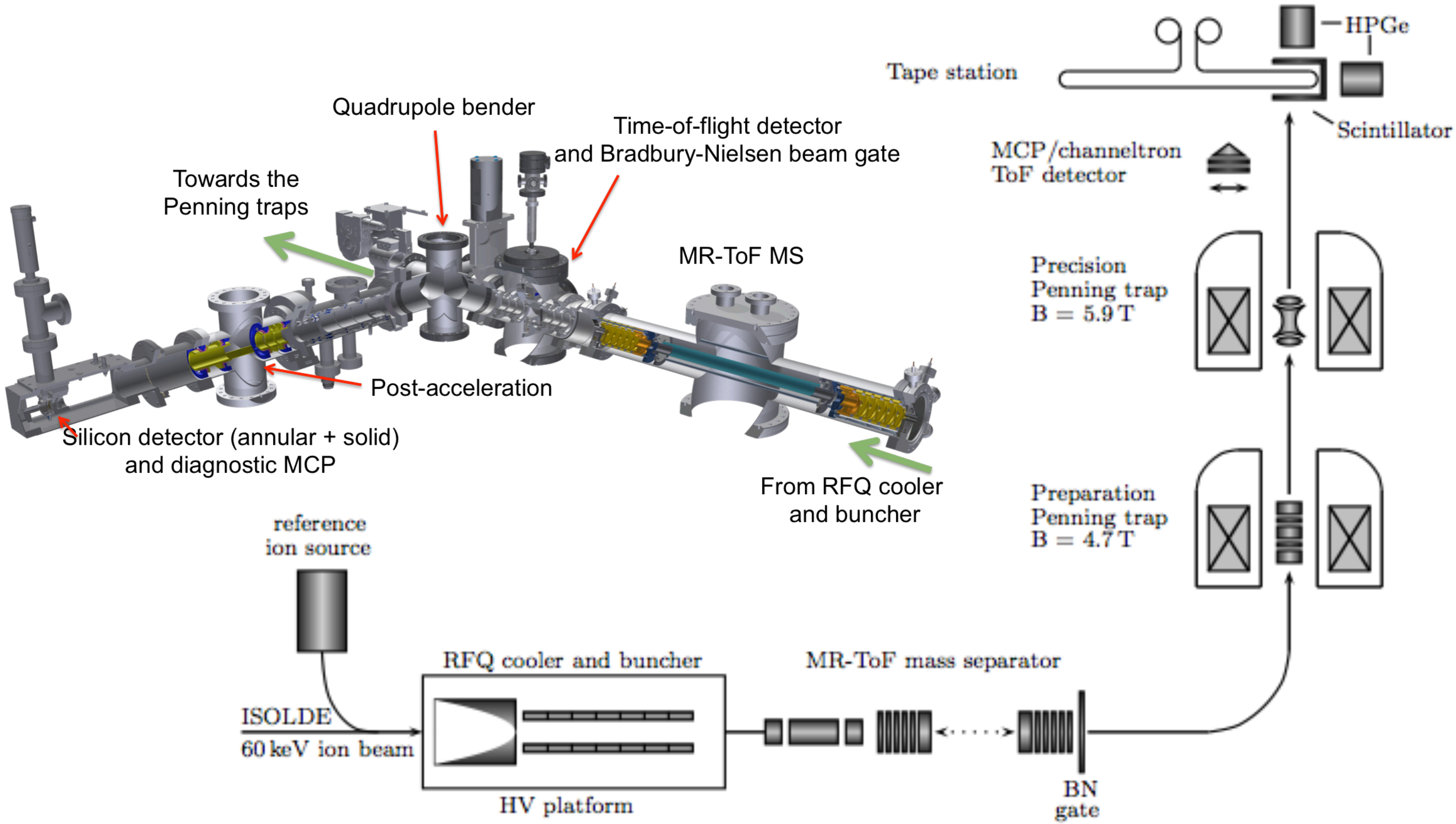


Mass measurement at ISOLTRAP



MR-ToF-MS-assisted decay: courtesy of N.A. Althubiti & F. Wienholtz

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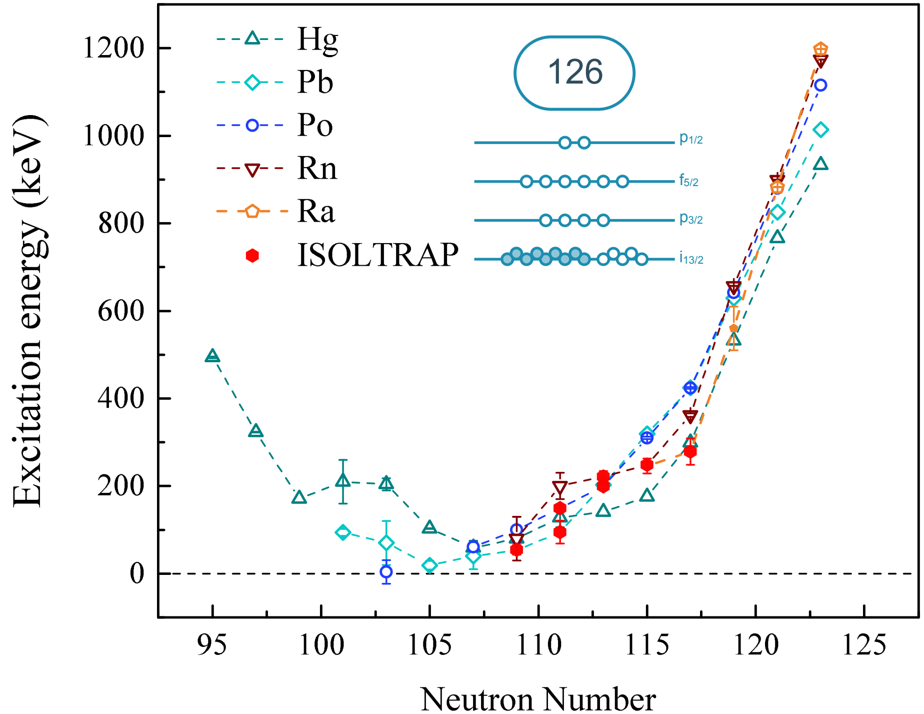
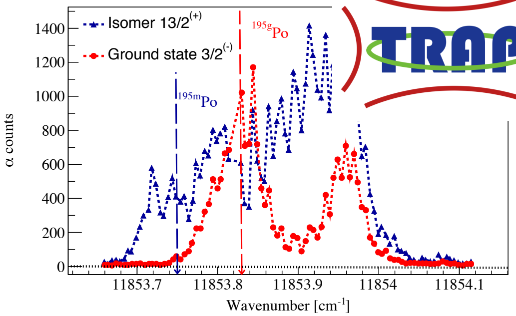
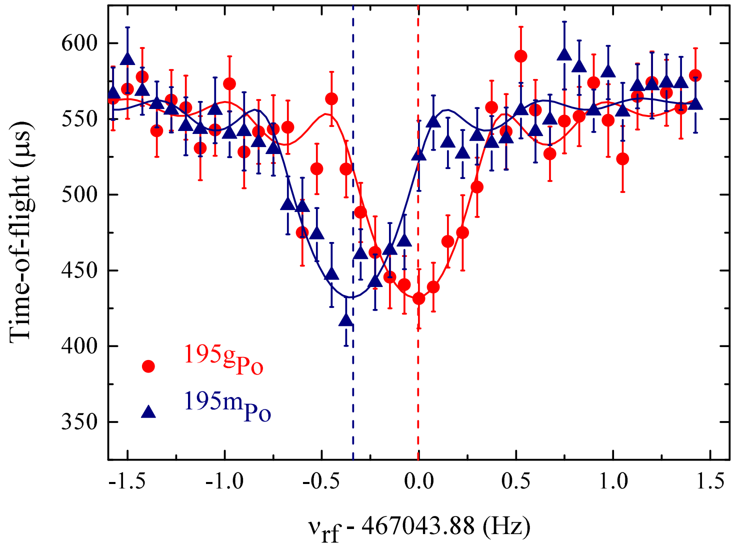
Mapping the 13/2+ isomer



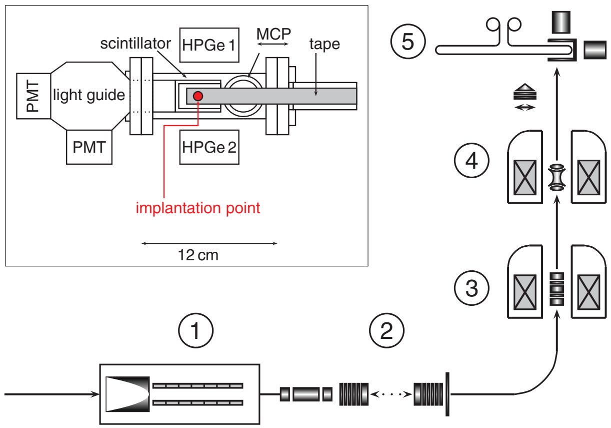


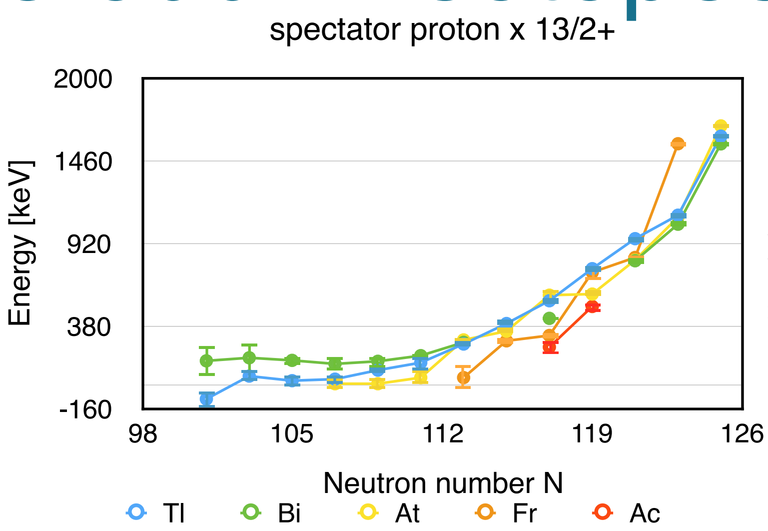


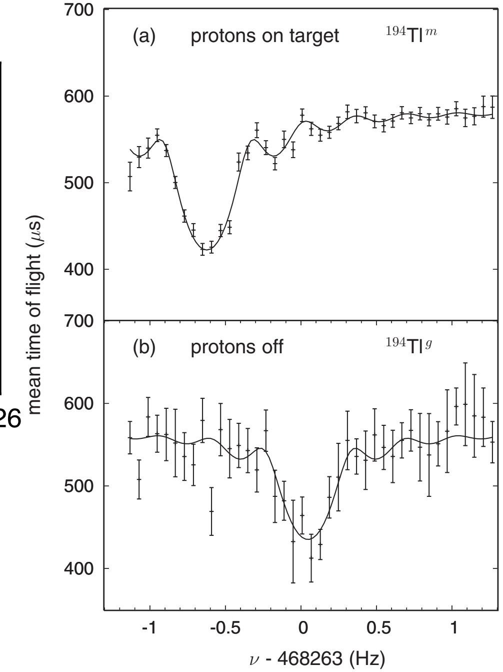
- Isomer selection with RILIS using the different hyperfine structures;
- Isobar (Tl) purification with the ISOLTRAP MR-ToF-MS;
- High-resolution Penning trap mass measurement of purified states;
- Daughter / mother isotope masses determined along the α-decay chain: Pb-Rn-Ra.

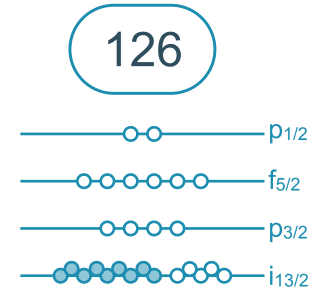
Po mass measurements: N.A. Althubiti et al., PRC in press.

Mapping the odd-A isotopes









- Isomer selection from the different production mechanisms (direct production vs. in-target decay);
- Isomer identification with decay spectroscopy behind the Penning trap;
- High-resolution Penning trap mass measurement of mixture of states;
- Full mapping of the 7⁺ state in the region.

*Tl mass measurements: J. Stanja et al., PRC **88**(2013)054304.*

Laser-assisted studies

- Laser spectroscopy can be used to purify a sample and even select an isomer.
- In-source laser spectroscopy is already sufficient to study heavy isotopes.
- Collinear Resonance Ionization Spectroscopy offers further possibilities across the whole nuclear landscape, but at some efficiency cost.

- In-depth studies have been performed on the polonium isotopes
  - ➡ Decay spectroscopy of ^{195,199}Po, in particular highlighting the evolution of the $5/2^-$ state in Po;
  - ➡ Mass measurement of ^{195,197,199}Po have revealed that the $13/2^+$ state never becomes the ground state across the Pb, Po, Rn, Ra isotopic chains.

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Summary

- Laser spectroscopy is a powerful tool to study ground state properties and to produce and purify radioactive ion beams.
- Around Z~82, extensive work has been performed and has revealed a reach amount of features in terms of shapes and sizes, using $\partial\langle r^2\rangle$ and Q_S alike.
- The comparison of isotonic chains shows a very different profile and more work is required to have absolute radii across the region. New programs have been initiated and hopefully more will follow.
- In the Z~82 region, the degeneracy between opposite parity states, involving especially the neutrons in the $i_{13/2}$ orbital, has been lifted by laser-assisted mass measurements.

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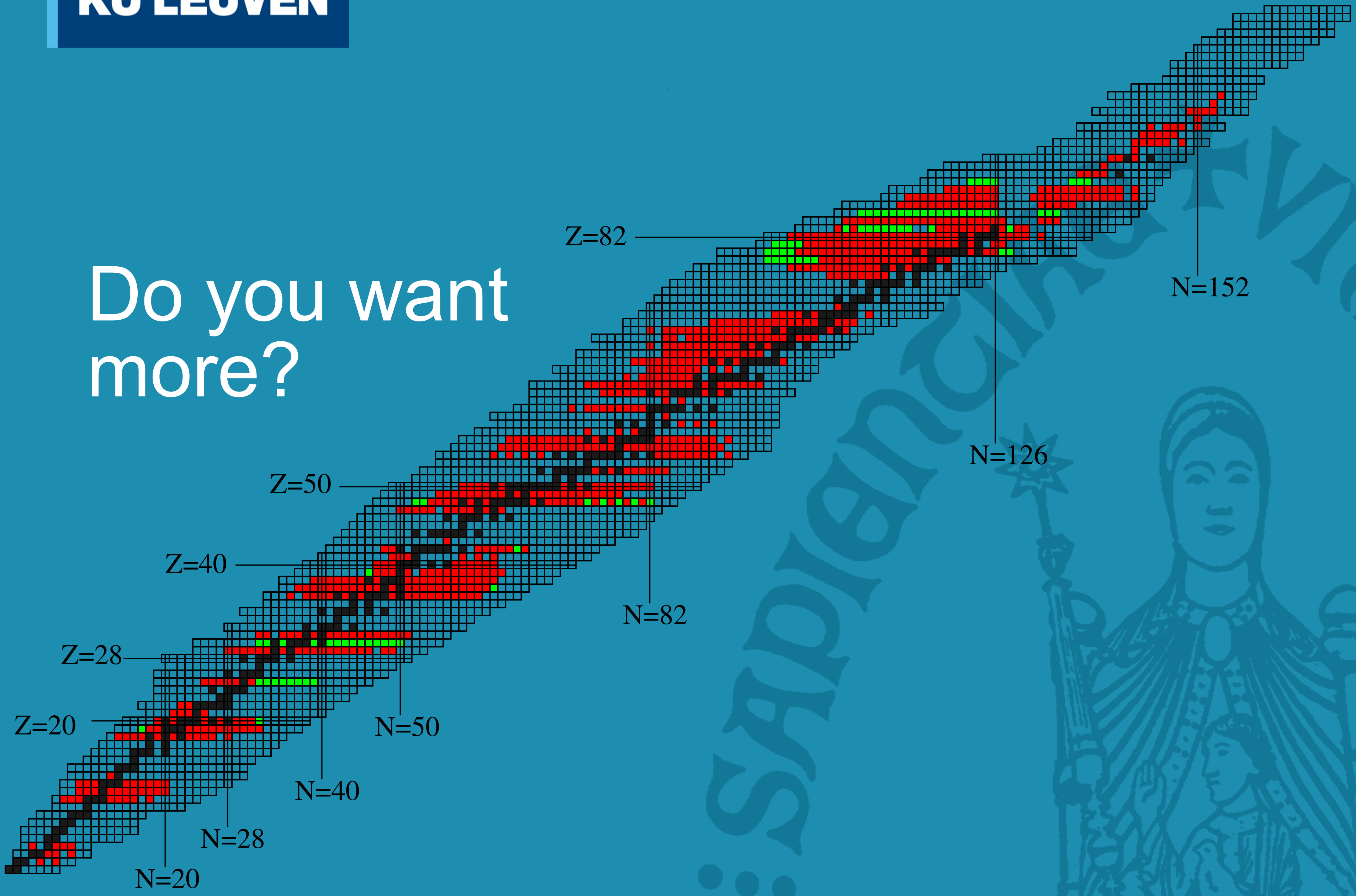
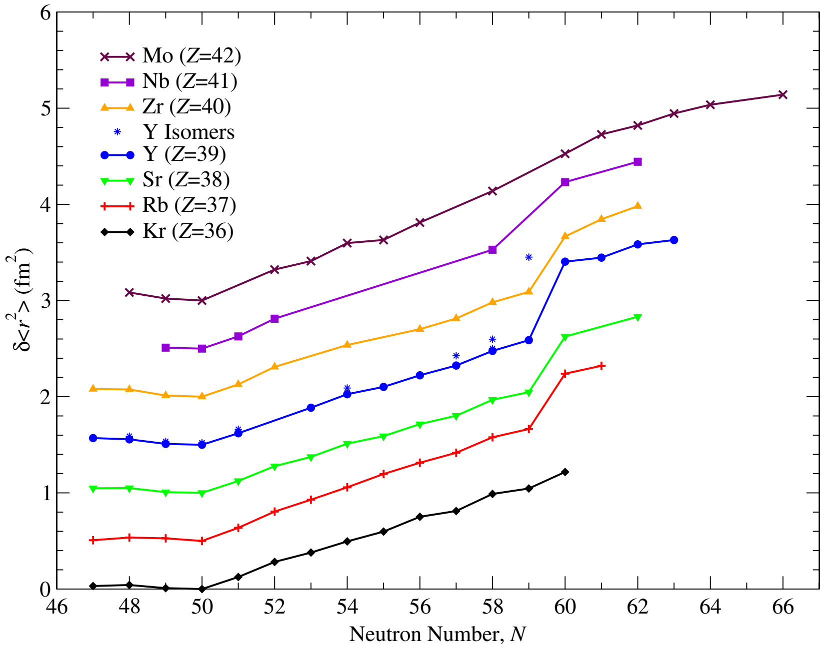
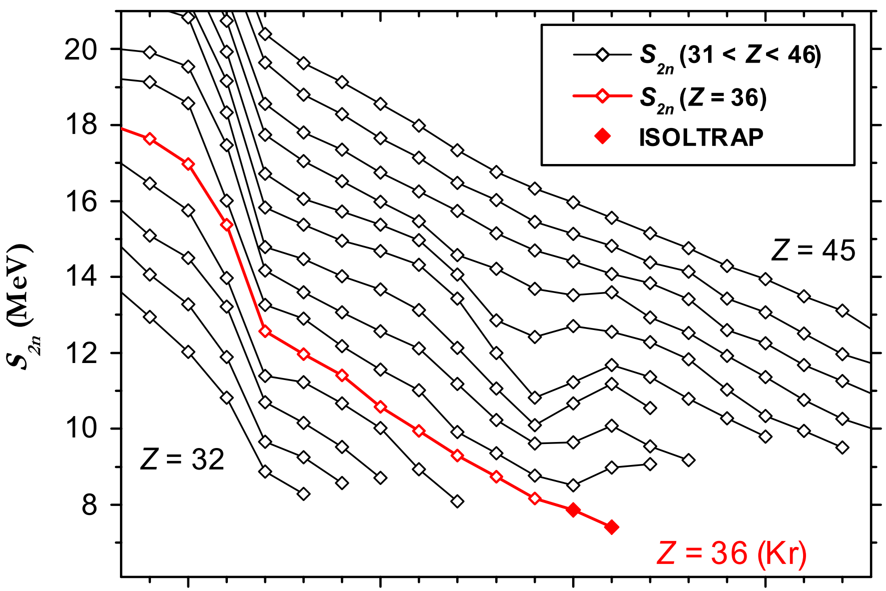
Do you want more?



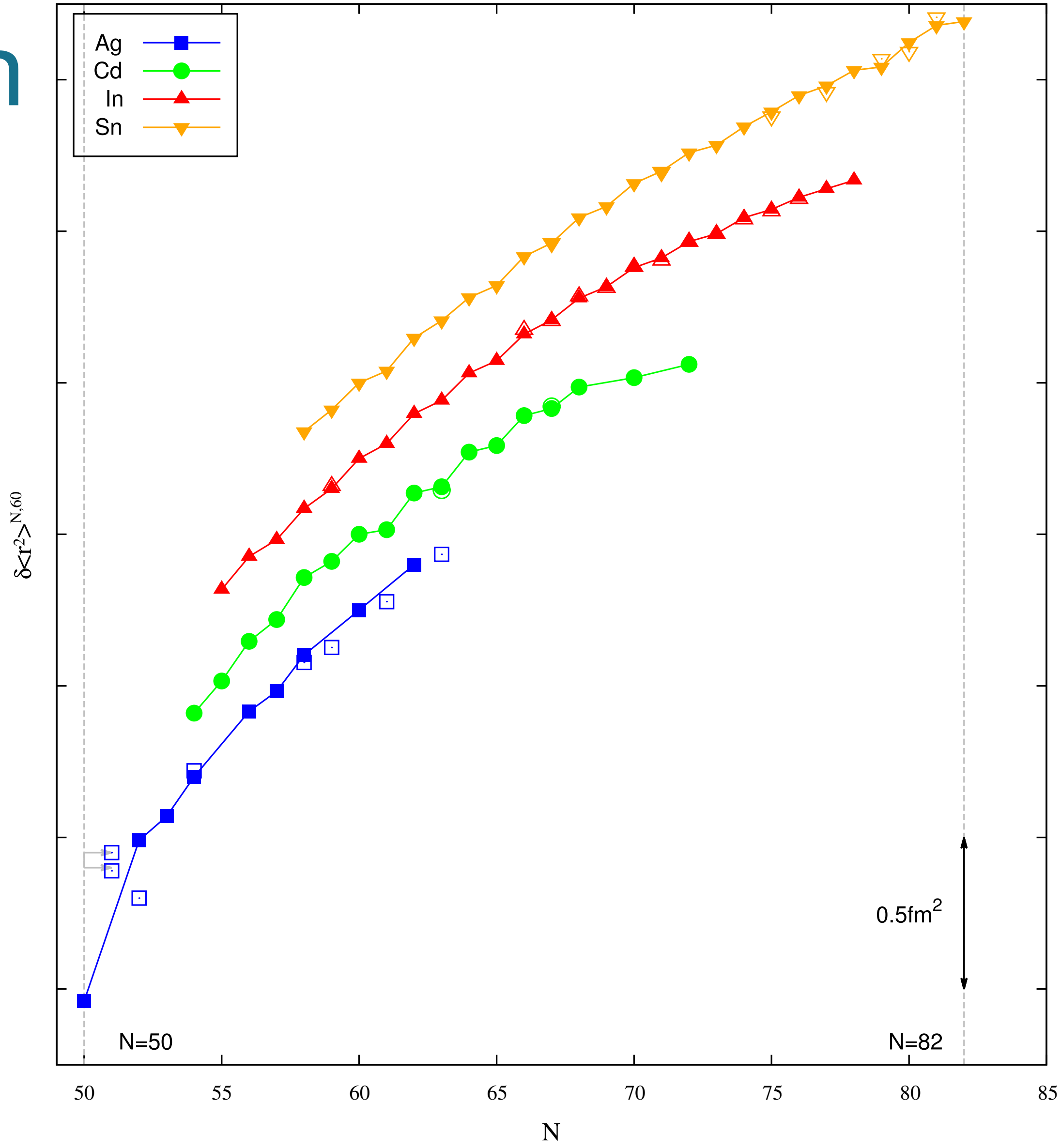
N~60 region





*Laser spec.: P. Campbell, I.D. Moore & M.R. Pearson, PPNP **86**(2016)127.*
*Mass meas.: S. Naimi et al., PRL **105**(2010) 032502.*

N~Z<50 region



Laser spec.: P. Campbell, I.D. Moore & M.R. Pearson, PPNP ***86****(2016)127.*
Ag.: R. Ferrer et al., PLB ***728****(2014)191.*

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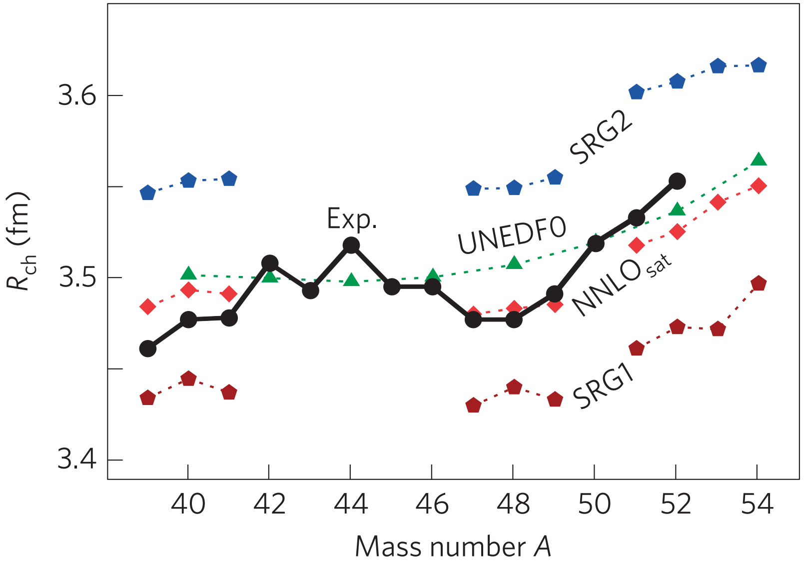
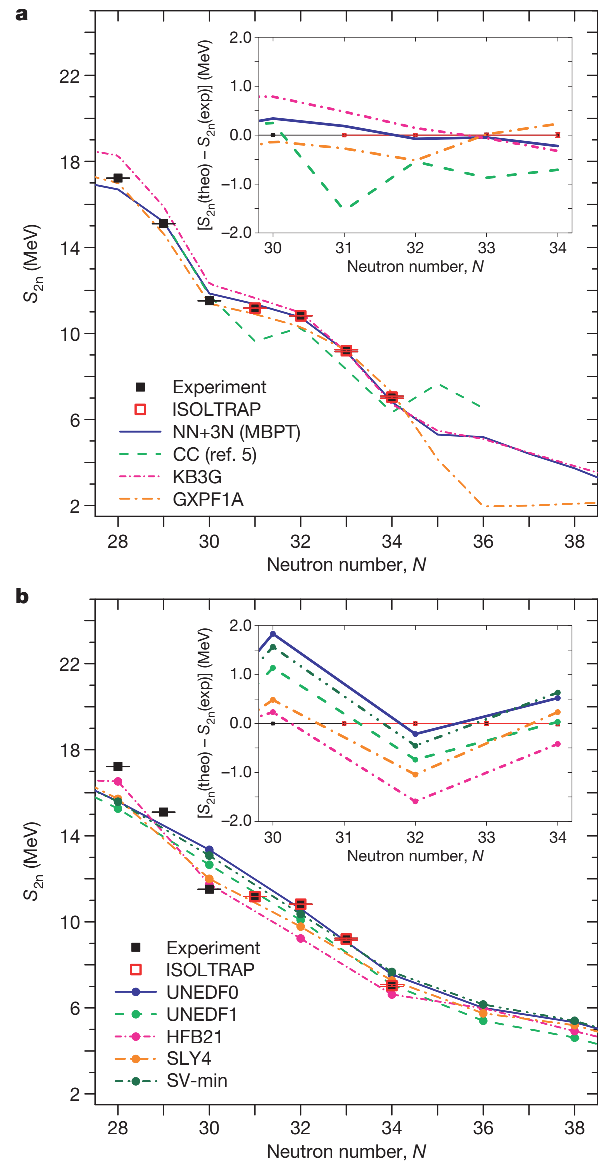
Ca isotopes





Laser spec.: R.F. Garcia Ruiz et al., Nature Physics **12**(2016)594.
Mass meas.: F. Wienholtz et al., Nature **498**(2013)346.