НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР **«КУРЧАТОВСКИЙ ИНСТИТУТ»**

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Национального исследовательского центра «Курчатовский институт»

50 ЛЕТ **НА ПИКЕ НАУКИ**

In-source laser spectroscopy of short-lived isotopes in the lead region

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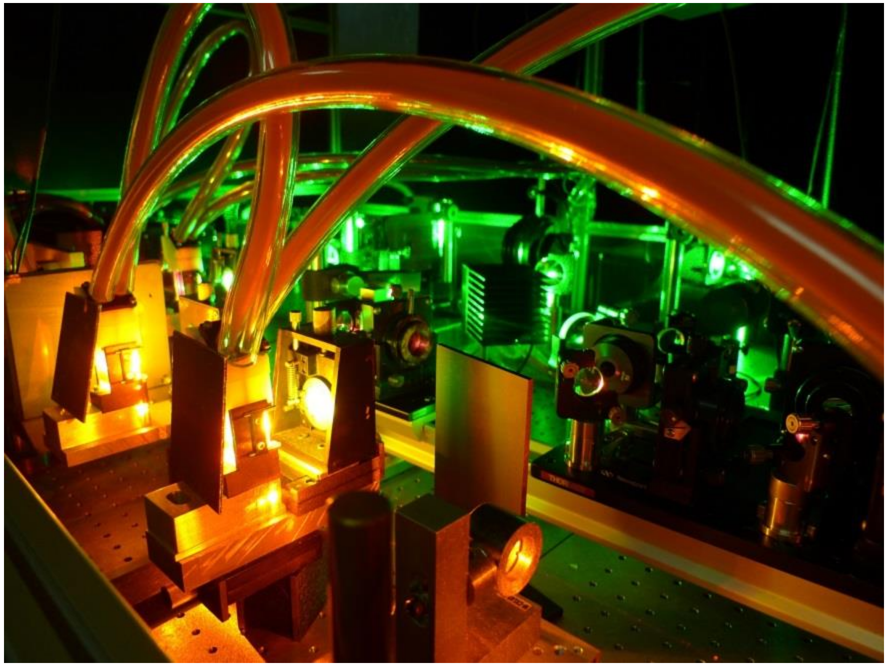
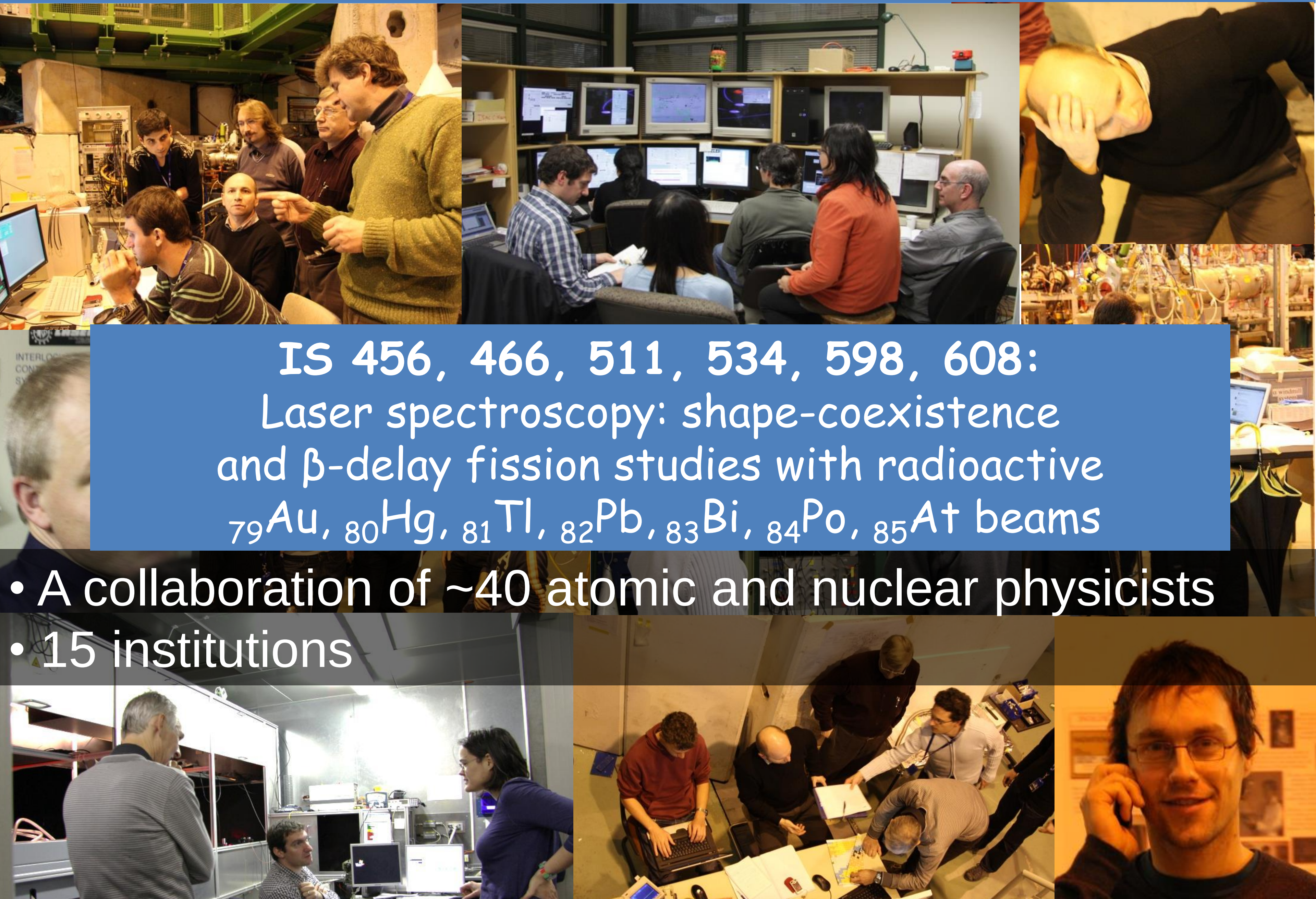


Windmill-ISOLTRAP-RILIS collaboration at ISOLDE (CERN)



IS 456, 466, 511, 534, 598, 608:

Laser spectroscopy: shape-coexistence and β-delay fission studies with radioactive $_{79}\mathrm{Au}$, $_{80}\mathrm{Hg}$, $_{81}\mathrm{Tl}$, $_{82}\mathrm{Pb}$, $_{83}\mathrm{Bi}$, $_{84}\mathrm{Po}$, $_{85}\mathrm{At}$ beams

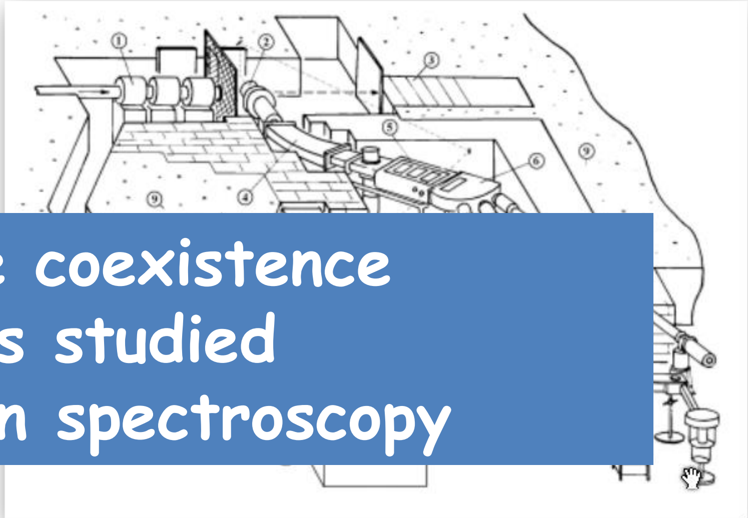
- A collaboration of ~40 atomic and nuclear physicists
- 15 institutions

IRIS facility at PNPI

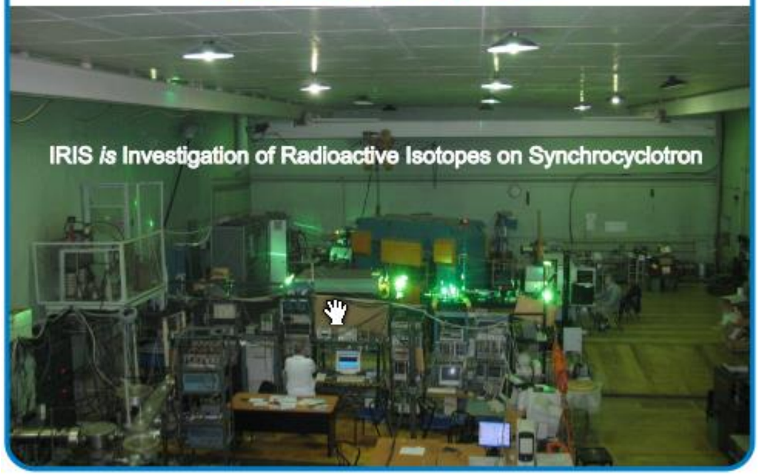
IRIS is ISOL installation working on-line with 1 GeV proton beam of PNPI synchrocyclotron

Shape evolution and shape coexistence for $_{81}$Tl и $_{83}$Bi isotopes studied by resonance laser ionization spectroscopy

IRIS facility (since 1975)



IRIS laboratory hall

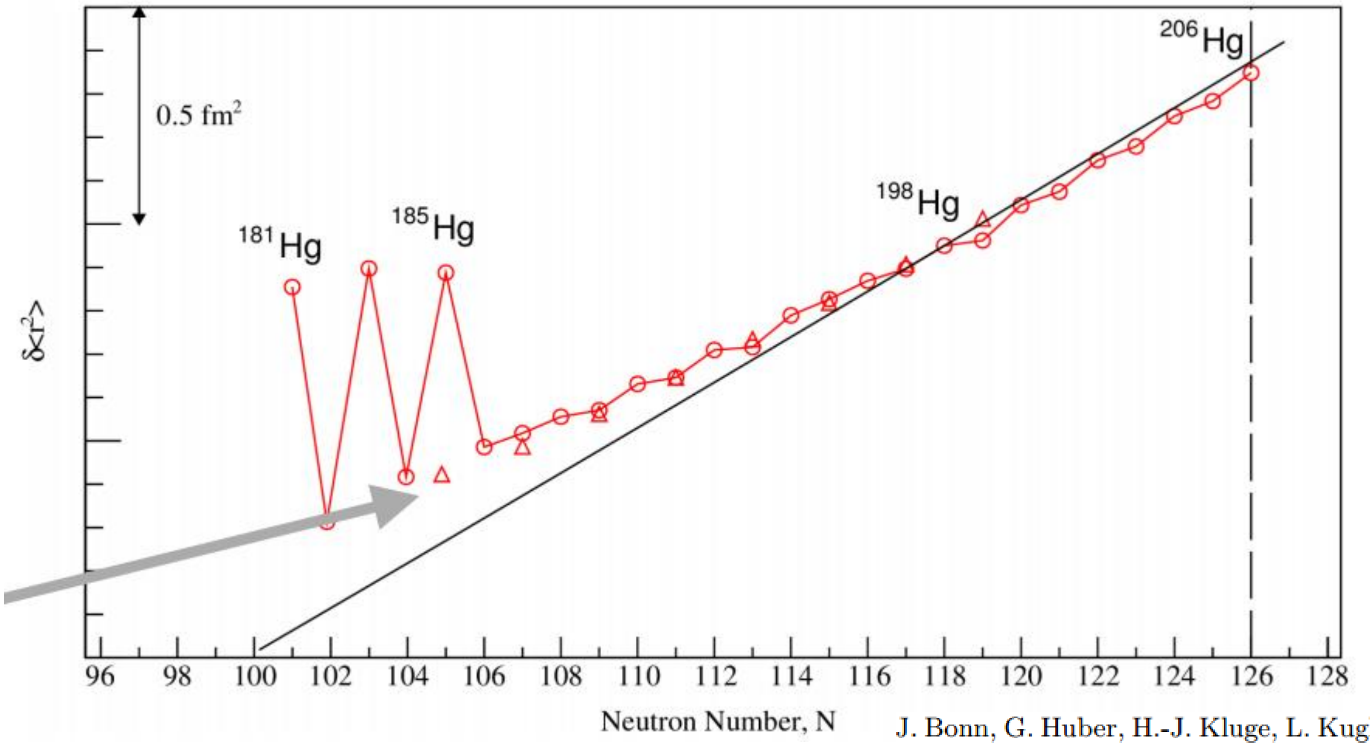


IRIS *is* Investigation of Radioactive Isotopes on Synchrocyclotron

Introduction

The shape and the size of a nucleus are among its most fundamental properties.
Usually, isotopic dependence of nuclear radii is smooth,
however, at the certain neutron numbers there are marked irregularities.

Isotope shift (IS) measurements in the lead region of $^{177-186}$Hg (Z = 80) near the neutron mid-shell at N = 104



J. Bonn, G. Huber, H.-J. Kluge, L. Kugler, and E. Otten, Phys. Lett. B **38**, 308 (1972).

This phenomenon was characterized as
“one of the most remarkable discoveries in nuclear structure physics in the last 50 years”.

K. Heyde and J. L. Wood, Phys. Scripta 91, 083008 (2016)

Motivation for the optical spectroscopy

Interpretation:

Sharp changes between nearly spherical shapes in the even-A cases and strongly-prolate deformed configurations in the odd-A isotopes

Assumption:

The neutron-deficient isotopes near Z = 82 (Pb-region) exhibit the richest manifestation of shape evolution and shape coexistence phenomena

Experimental tasks:

- ✓ to extend of mercury measurements down to ^{180}Hg and beyond
- ✓ to investigate the ground and isomeric states shapes for different Z's in Pb-region

Experimental challenge

The center of Pb-region lies far from stability:

- ✓ low production cross sections
- ✓ overwhelming production of isobaric contaminants
- ✓ very short half lives of most nuclei of interest

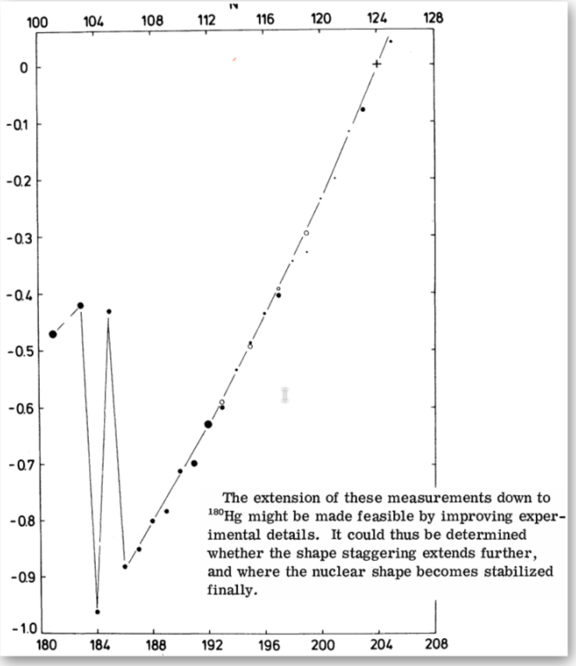
Conclusion

For experimental investigations in Pb-region should be used the most extreme methods ever developed for far-from-stability nuclear structure study

Solution

- ✓ Measurements at ISOL facilities
  - large production yield rates from the thick targets
  - ionization enhancement in *laser ion source*
- ✓ Using of the optical spectroscopy technique as very sensitive tool

Nuclear shape staggering

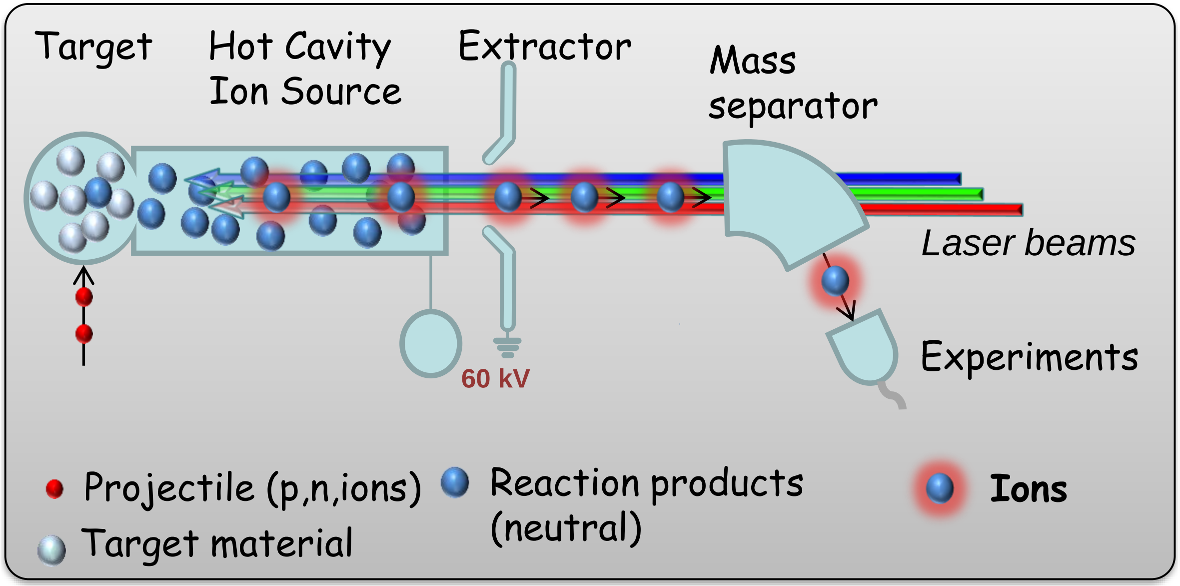


The extension of these measurements down to ^{180}Hg might be made feasible by improving experimental details. It could thus be determined whether the shape staggering extends further, and where the nuclear shape becomes stabilized finally.

RIB Production at ISOL facilities

ISOL technique step-by-step:

- ✓ Production of the radioactive isotopes in target
- ✓ Ionization in hot cavity
- ✓ Extraction from the target - ion source system
- ✓ Mass separation
- ✓ Transport to experimental setups



Target

Hot Cavity Ion Source

Extractor

Mass separator

60 kV

Laser beams

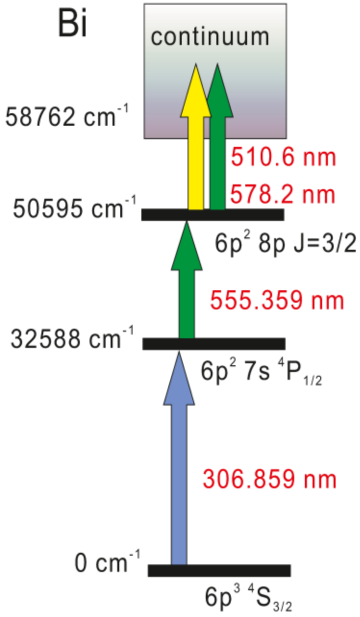
Experiments

● Projectile (p,n,ions)

● Reaction products (neutral)

● **Ions**

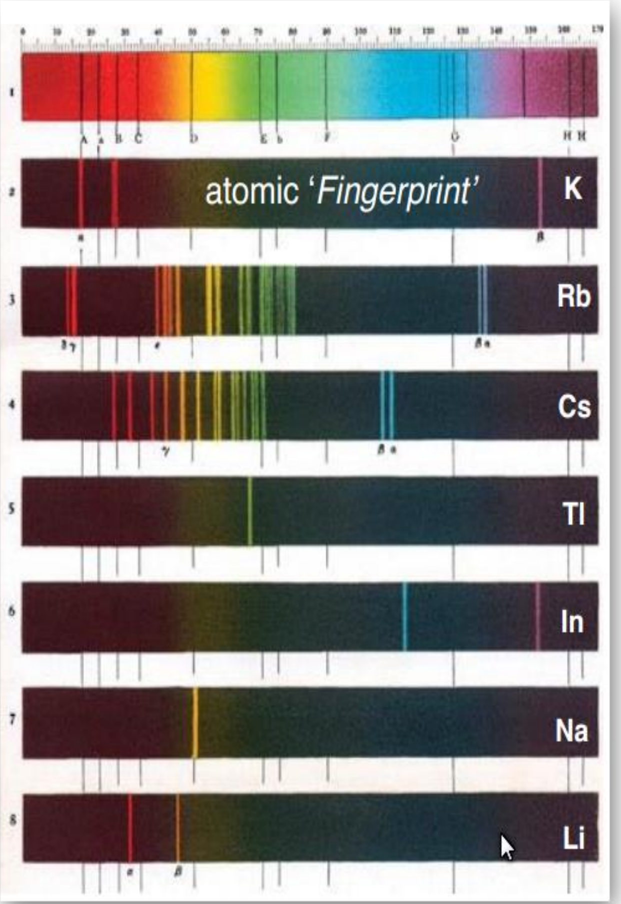
● Target material



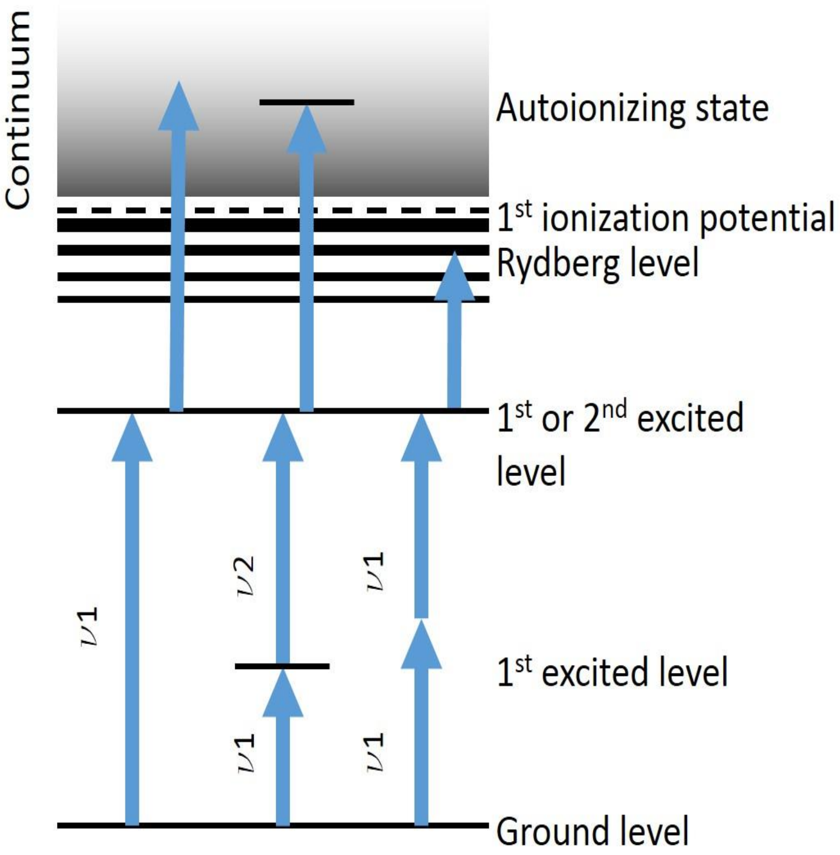
Due to its high efficiency (from 1 to 30%) *Laser Ion Source* is very appropriate at ISOL facilities for:

- ✓ RIB production
- ✓ atomic spectroscopy of rare isotopes, produced in very small quantities

Method of resonance laser ionization



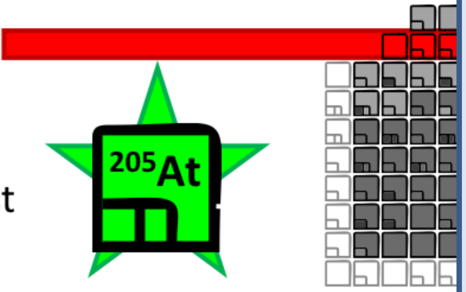
The position of the excited levels is specific for each element



The essential point of the method: step-by-step resonant laser excitation from the ground state through intermediate states to autoionization state or the continuum

Tuning the laser wavelengths to this "fingerprint" provides an ionization method with **high elemental selectivity**

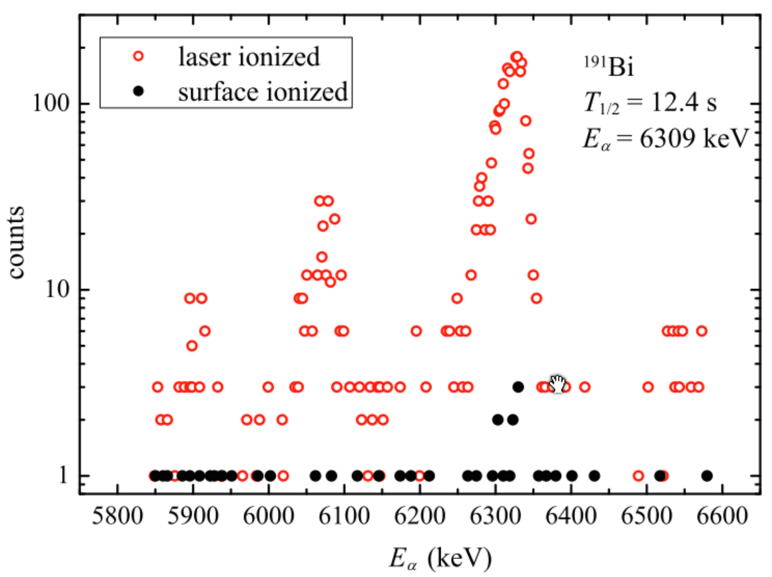
Resonance Laser Ionization at ISOL facilities



isobar selectivity
after ***Laser IS***

Isotope of interest

By enhancing only one element of interest over a broad range of contaminants,
- ✓ cleaner conditions are reached
- ✓ more accurate studies can be performed



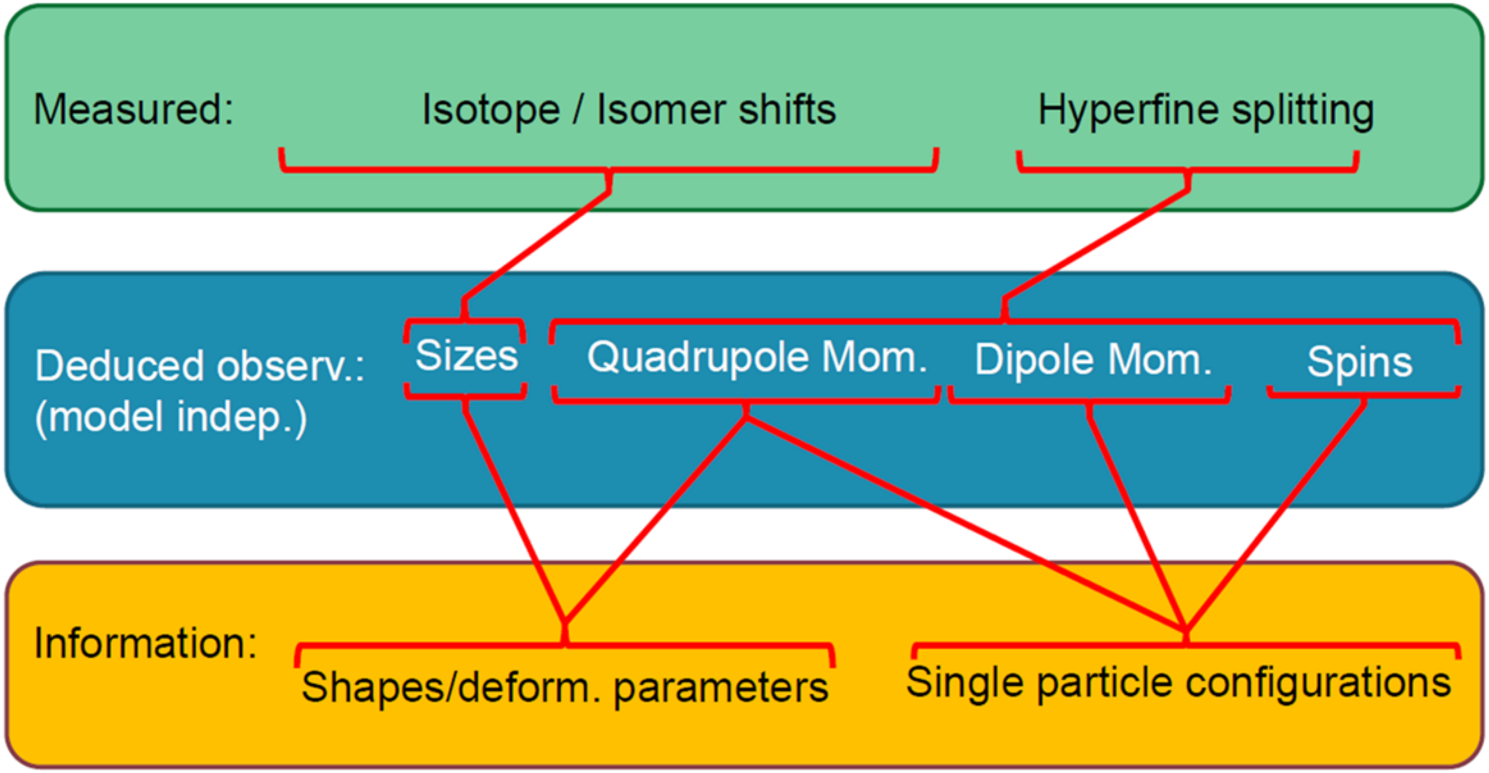
Examples of experimental alpha-spectra collected in “laser-on” and “laser-off” regimes

The method of resonance laser photoionization in LIS – efficient tool for production of **clean RIB** at ISOL facilities

Laser Spectroscopy Observables for Nuclear Physics

Isotope shift (IS) measurements
give the variation of the mean square charge radii $\delta\langle r^2\rangle$ along an isotopic chain ⇒ **Shape and size of nuclei, nuclear shape deformation**

Measurements of hyperfine splitting (HFS)
of atomic lines give the nuclear magnetic dipole and electric quadrupole moments ⇒ **Nuclear structure, nuclear shape deformation**



Measured: Isotope / Isomer shifts; Hyperfine splitting

Deduced observ.: (model indep.) Sizes; Quadrupole Mom.; Dipole Mom.; Spins

Information: Shapes/deform. parameters; Single particle configurations

Nuclear Charge Radius and Nuclear Deformation

$$\langle r^2 \rangle = \frac{\int_0^\infty \rho(\vec{r})\, r^2 d^3r}{\int_0^\infty \rho(\vec{r})\, d^3r}$$

mean-square nuclear charge radius (mscr)

in terms of the spherical harmonics:

$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \sum_{i=2}^{\infty} \langle \beta_i^2 \rangle \right) \qquad \langle r^2 \rangle \approx \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \langle \beta_2^2 \rangle \right)$$

$<r^2>_0$ - mean-square charge radius of a spherical nucleus of identical volume
(Usually for the evaluation the droplet model is used)
$<\beta_i>$ - deformation parameters of order i

Main isotopic trend of *mscr* is described by the Droplet Model.
Deviations from the DM trend are attributed to the advance of the mean-square quadrupole deformation

Influence of the nuclear deformation on changing of charge radii:

$$\delta \langle r^2 \rangle^{A,A'} = \delta \langle r^2 \rangle_0^{A,A'} + \langle r^2 \rangle_0 \cdot \frac{5}{4\pi} \delta \langle \beta_2^2 \rangle^{A,A'}$$

Motivations for the optical nuclear spectroscopy

- extreme sensitivity of $\delta <r^2>$ to changes in the nuclear shape
- model-independence of $\delta <r^2>$ extraction
- isotopes in which it can be measured

Nuclear Charge Radius and Isotope Shift (IS)

$\boxed{\delta\nu^{A,A'}} = \delta\nu_F^{A,A'} + \delta\nu_M^{A,A'}$ - isotope shift of optical line

$\delta\nu_F^{A,A'} = \boxed{F}\underline{\delta\langle r^2\rangle_{A,A'}}$ - mean-square charge radius

$$\delta\nu_M^{A,A'} = \frac{M(A-A')}{AA'}$$

$$M = M^{\mathrm{NMS}} + \boxed{M^{\mathrm{SMS}}}$$

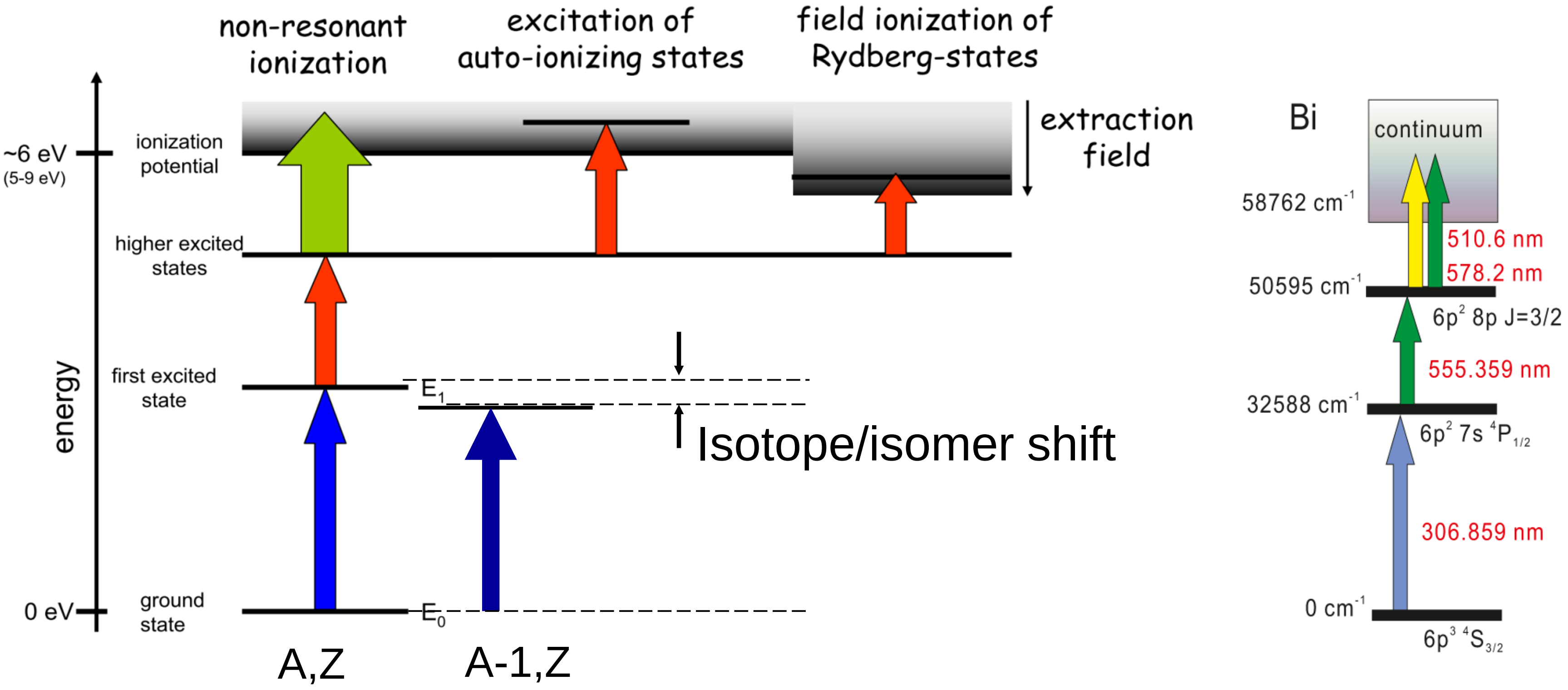
🟨 - experiment

🟩 - calculations

The isotope shift contains a contribution from the difference in the mean square charge radius between the two isotopes but it is not always an easy task to extract this information.

For bismuth isotopic chain **advanced atomic and molecular calculations** should be used for determination of electronic factor F and for evolution of specific mass shift constant M^{SMS}

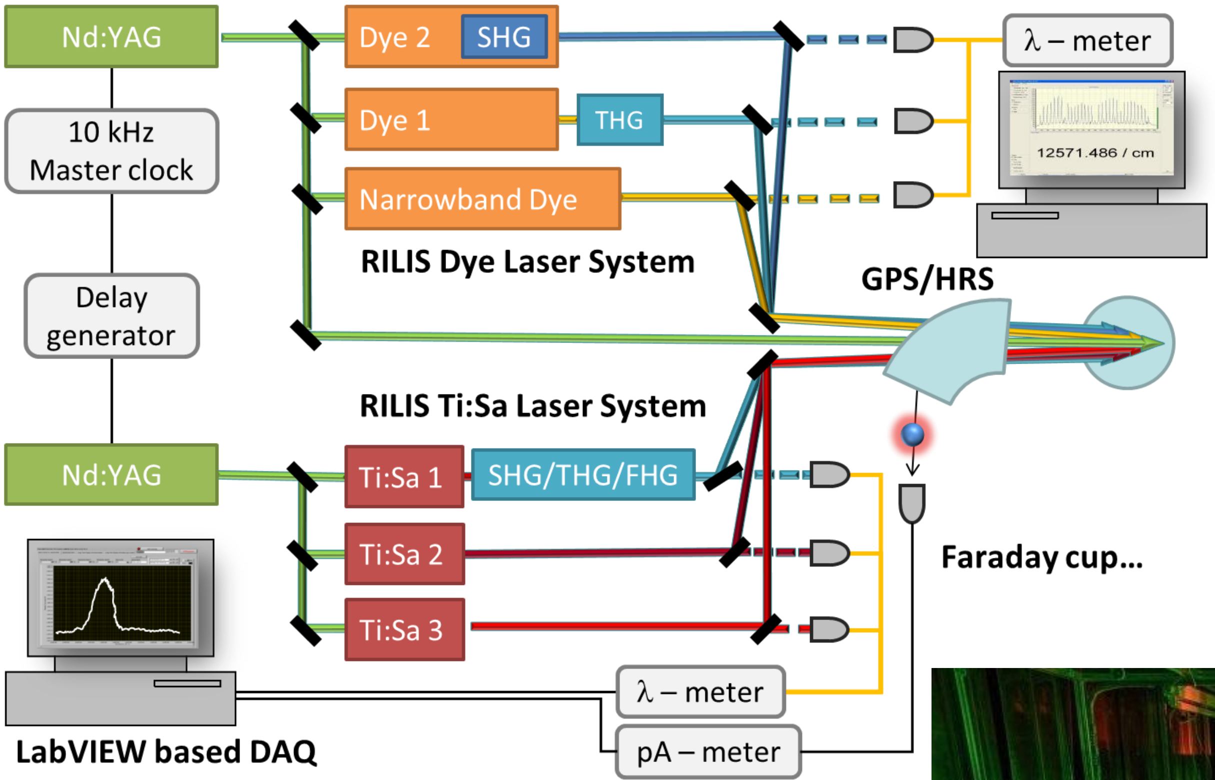
Method of resonance laser ionization



Isotope shift (IS), hyperfine structure (HFS) measurements:

By scanning the narrow-band laser frequency over the resonance, together with simultaneous counting of the mass-separated photo-ions, the **isotope shifts** and **hyperfine structure** of the atomic spectral lines can be measured

ISOLDE RILIS laser system



Nd:YAG

10 kHz Master clock

Delay generator

Nd:YAG

Dye 2

SHG

Dye 1

THG

Narrowband Dye

RILIS Dye Laser System

λ – meter

12571.486 / cm

GPS/HRS

RILIS Ti:Sa Laser System

Ti:Sa 1

SHG/THG/FHG

Ti:Sa 2

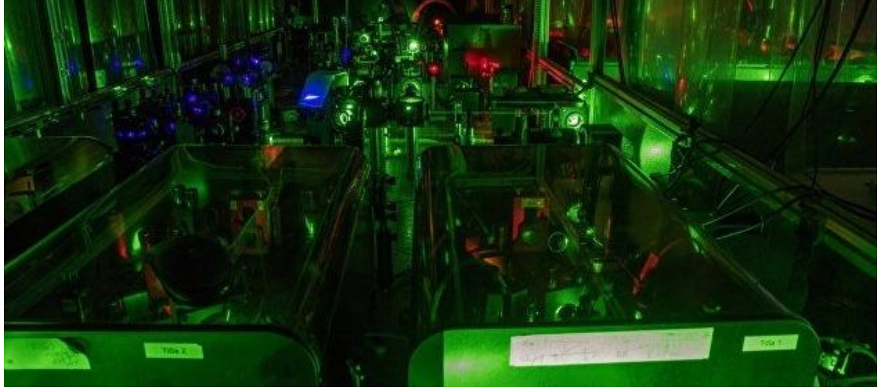
Ti:Sa 3

Faraday cup…

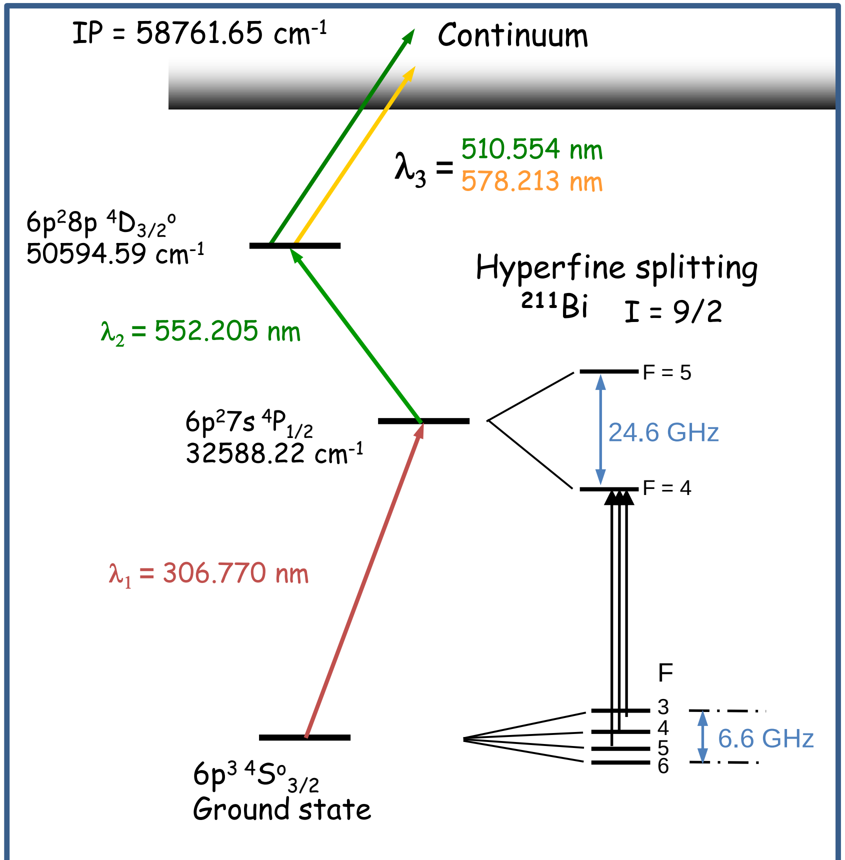
λ – meter

pA – meter

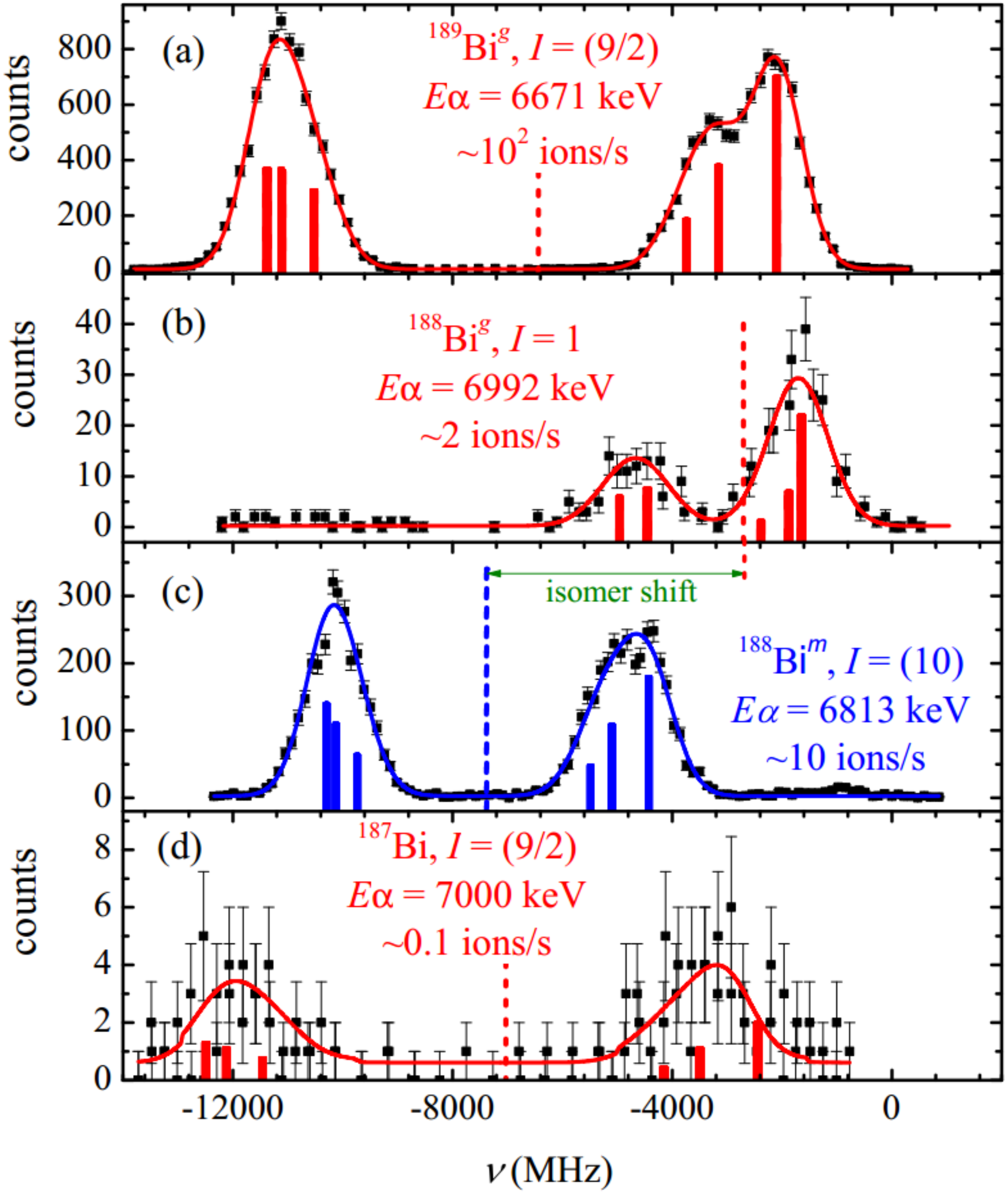
LabVIEW based DAQ



Bi experimental spectra



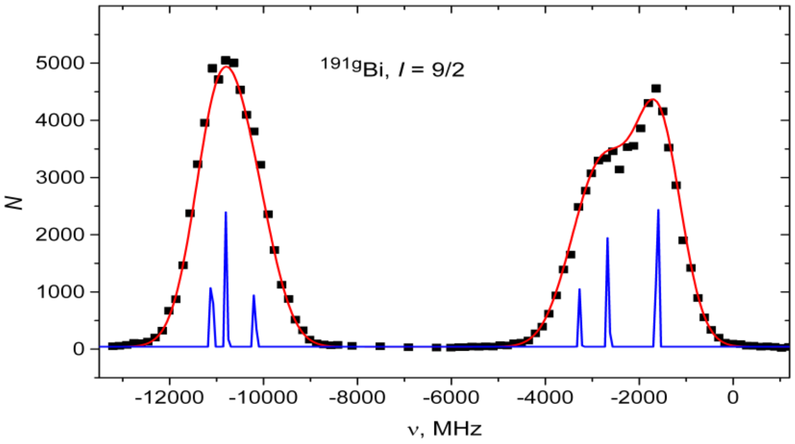
Bi ionization scheme

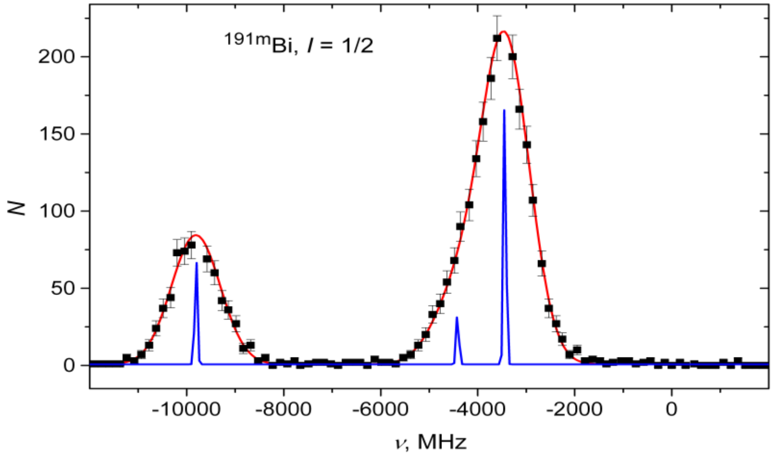


Shift of the centre of hfs gives isotope shift

Distance between peaks gives hfs splitting

Positions of the hfs components on the spectrum

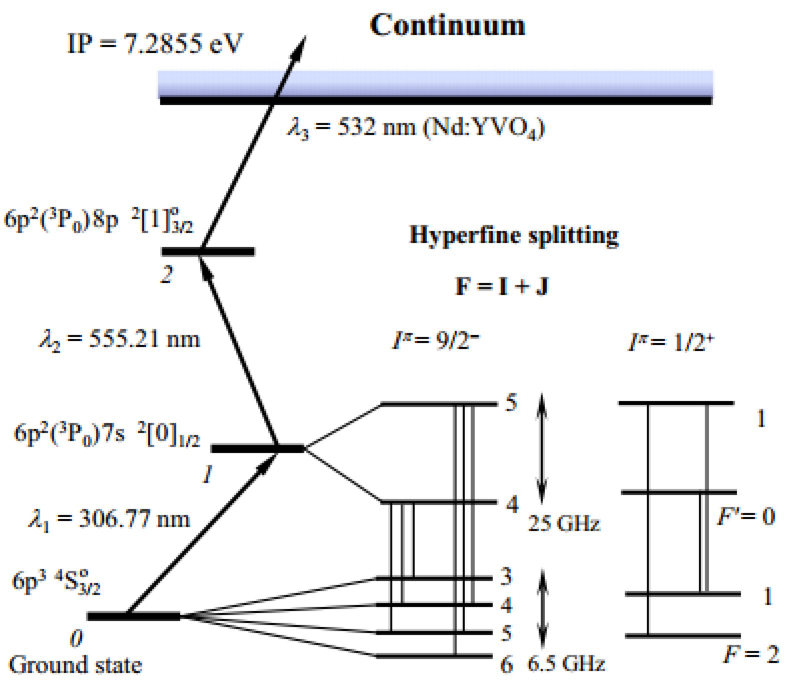




$$\nu_{F,F'} = \nu_0 + \Delta\nu_{F'} - \Delta\nu_F$$

ν_0 - the position of the center of gravity of the hfs,
the prime symbol denotes the upper level of the transition

hyperfine structures for the states
with nuclear spins I = 1/2 and I = 9/2
typical for neutron deficient Bi isotopes



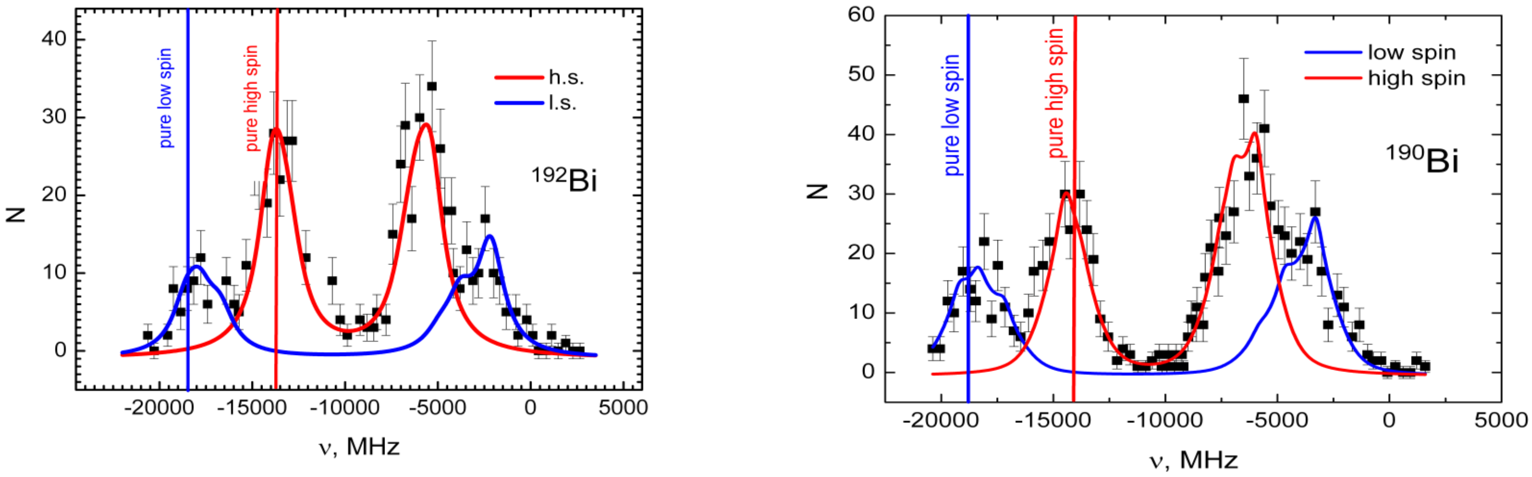
$$\Delta\nu_F = A\cdot\frac{K}{2} + B\cdot\frac{0.75\cdot K\cdot(K+1) - I\cdot(I+1)\cdot J\cdot(J+1)}{2\cdot(2I-1)\cdot(2J-1)\cdot I\cdot J}$$

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

$$\vec{F} = \vec{I} + \vec{J}, \quad F = |I-J|, |I-J|+1, \ldots, I+J$$

$$A \propto \mu, \quad B \propto Q$$

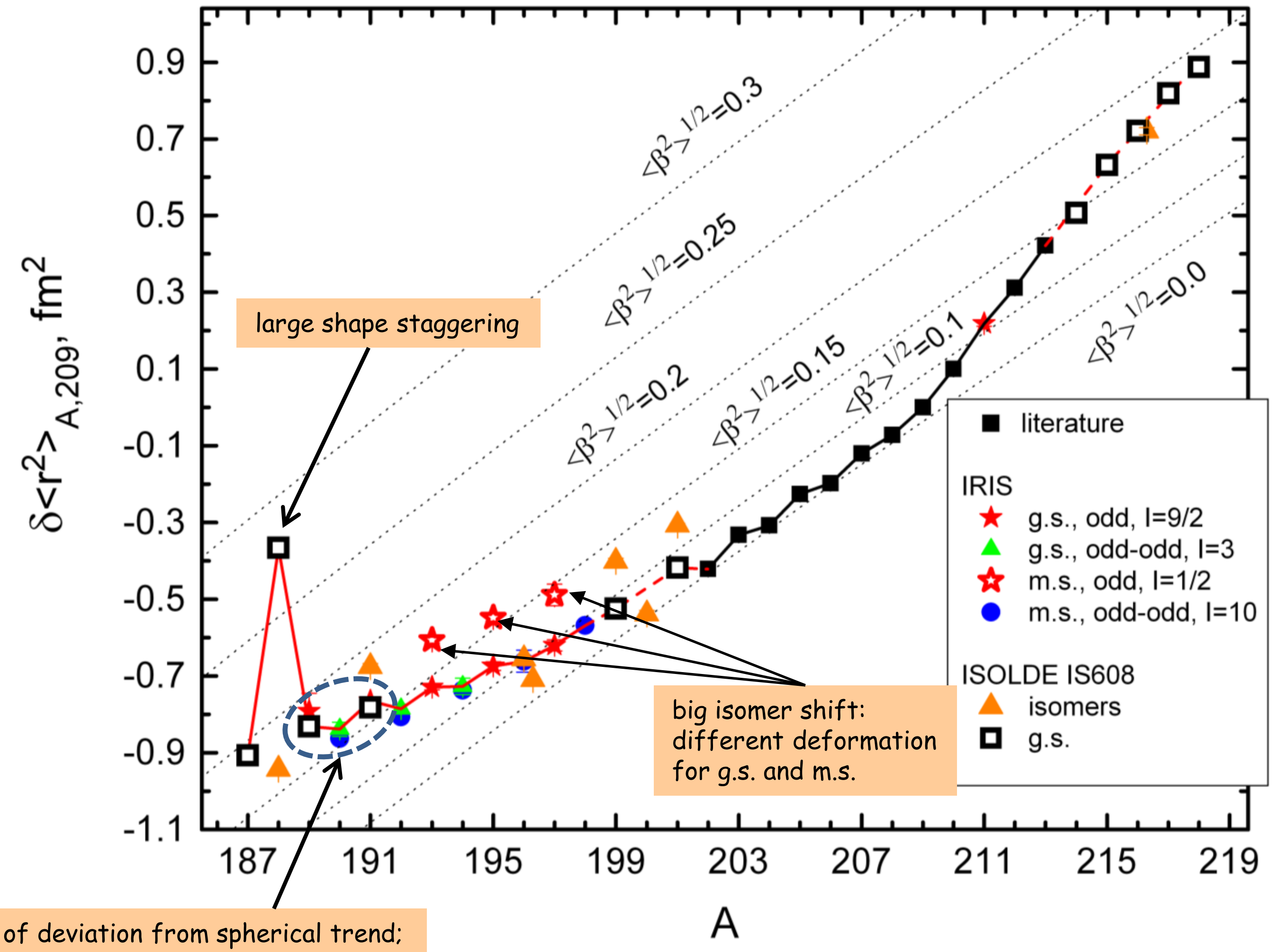
Bi: possibility of isomer selectivity



Hfs spectra for two isomers in $^{190,\,192}$Bi.
Vertical lines mark the frequency positions for the narrow-band 1st step laser with the pure low-spin (blue) or high-spin (red) isomer production.

⇨ possibility of the first isomer selective βDf studies

Bi: radii (3 effects)



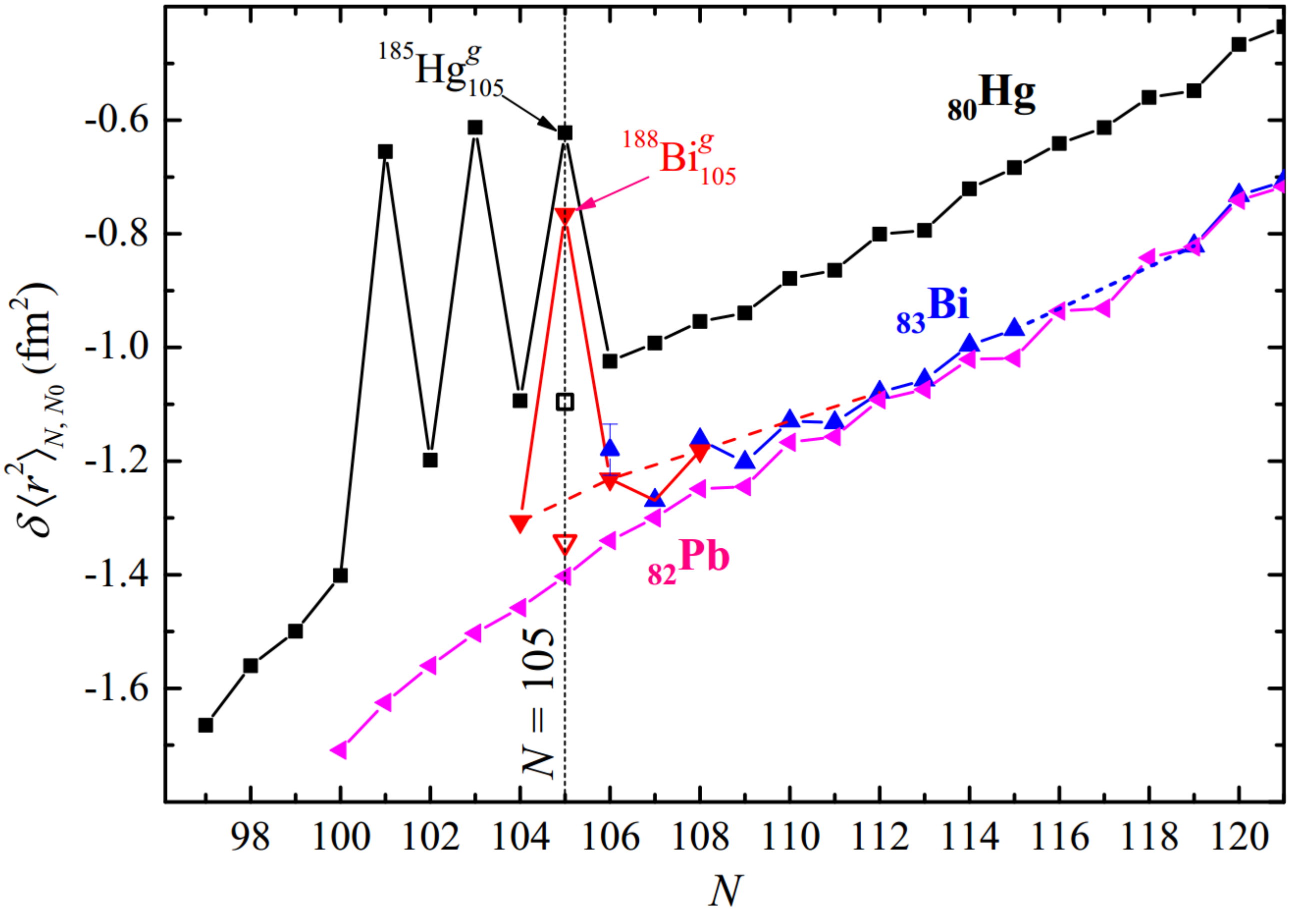
large shape staggering

big isomer shift: different deformation for g.s. and m.s.

start of deviation from spherical trend; big odd-even staggering

$$\delta\left\langle r^2\right\rangle^{A,A'} = \delta\left\langle r^2\right\rangle_0^{A,A'} + \left\langle r^2\right\rangle_0 \cdot \frac{5}{4\pi}\delta\left\langle \beta_2^2\right\rangle^{A,A'}$$

Bi & Hg: large shape staggering

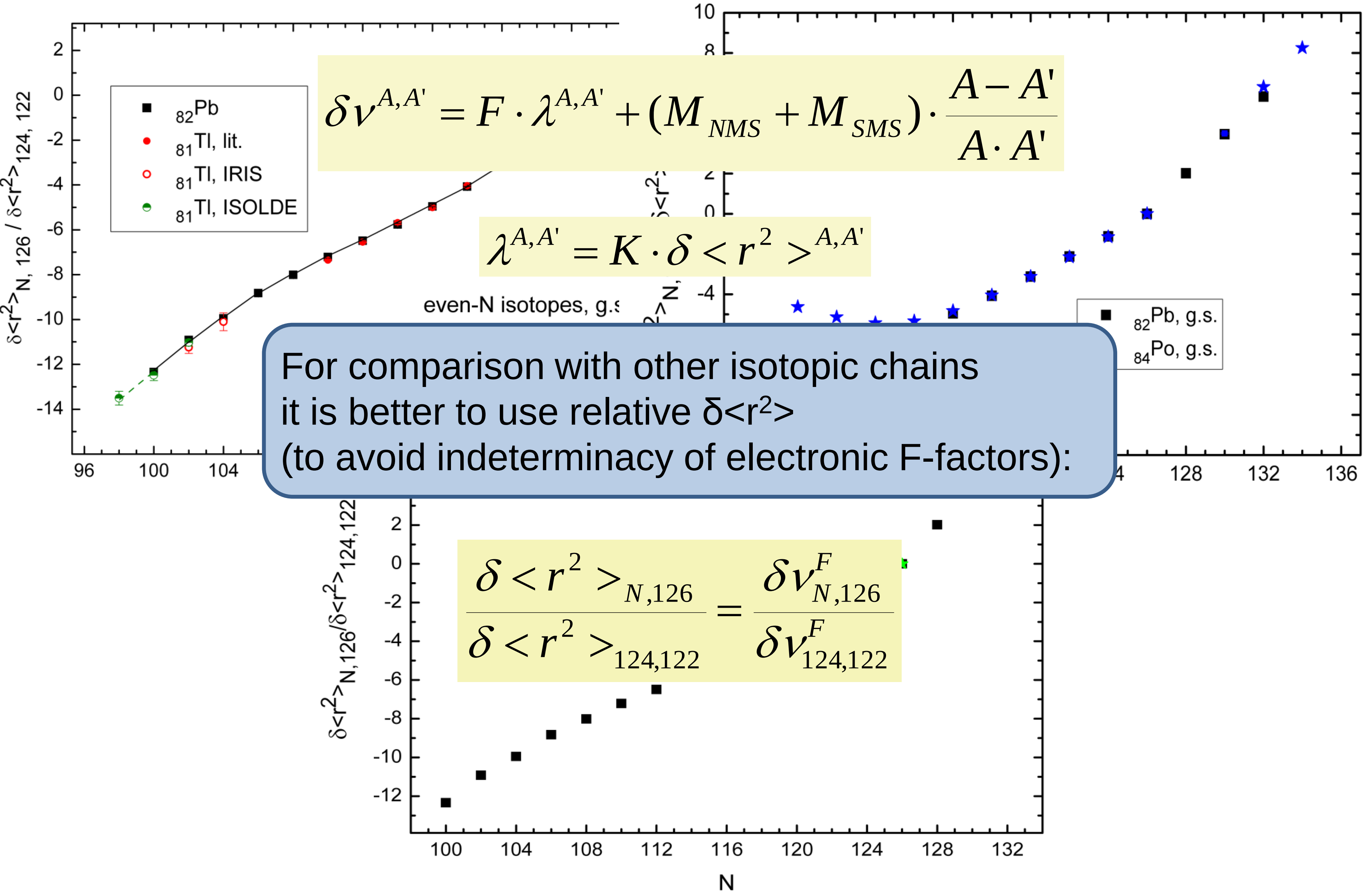


By performing laser-spectroscopy studies of $^{187-191}Bi$, we demonstrated a sharp radius increase for $^{188}Bi^{g}$, relative to the neighboring $^{187,189}Bi^{g}$.

Fifty years after discovery of shape-staggering in Hg, we have found only the second example of such an unusual behavior, now in the lightest Bi (Z = 83) isotopes with odd number of protons.

This dramatic change happens at the same neutron number (N = 105), where the huge shape staggering started in the isotonic ^{185}Hg, and it has the same magnitude.

Relative radii: Comparison of Tl, Pb and Po



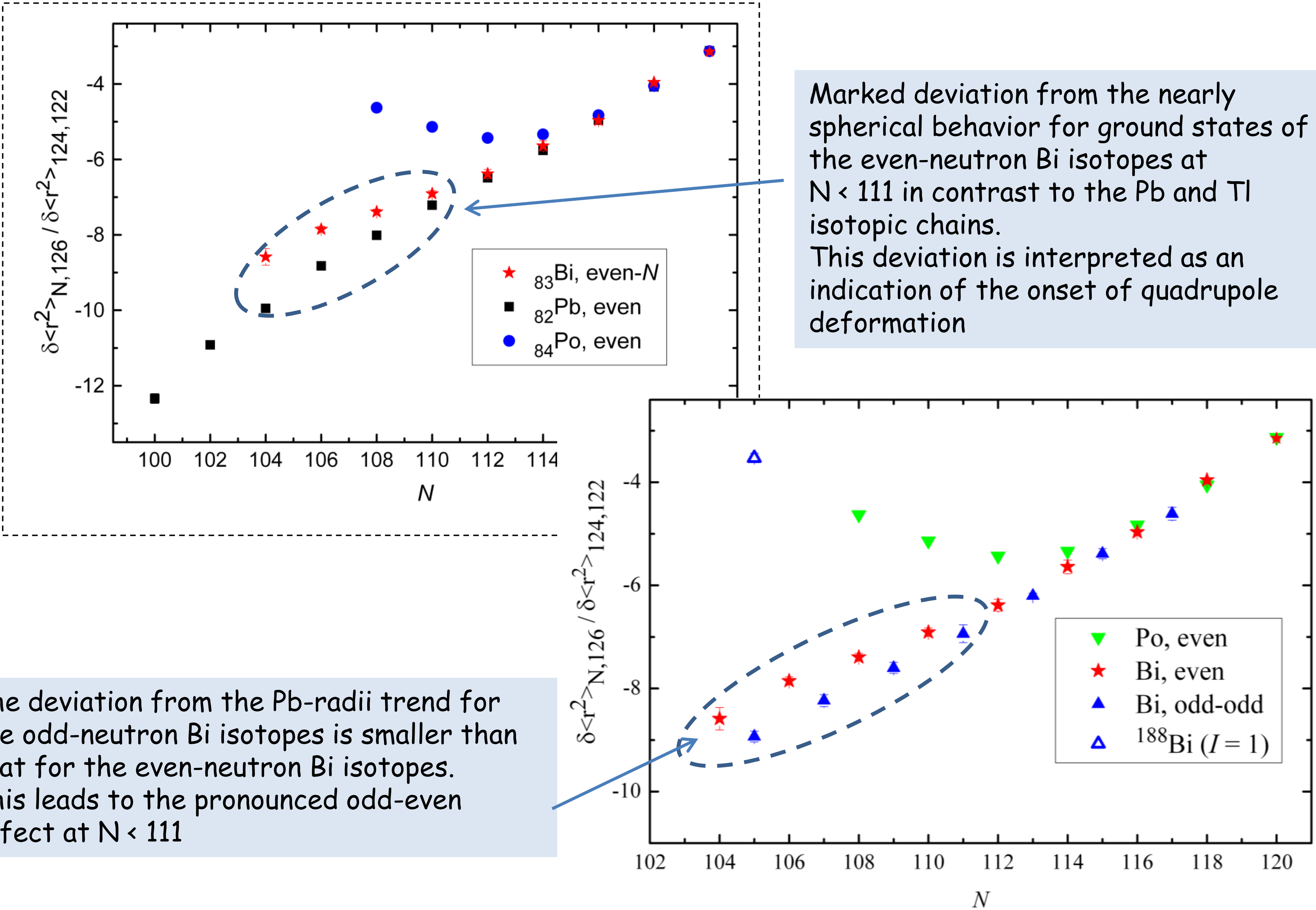
$$\delta\nu^{A,A'} = F \cdot \lambda^{A,A'} + (M_{NMS} + M_{SMS}) \cdot \frac{A - A'}{A \cdot A'}$$

$$\lambda^{A,A'} = K \cdot \delta < r^2 >^{A,A'}$$

For comparison with other isotopic chains
it is better to use relative $\delta<r^2>$
(to avoid indeterminacy of electronic F-factors):

$$\frac{\delta < r^2 >_{N,126}}{\delta < r^2 >_{124,122}} = \frac{\delta\nu^F_{N,126}}{\delta\nu^F_{124,122}}$$

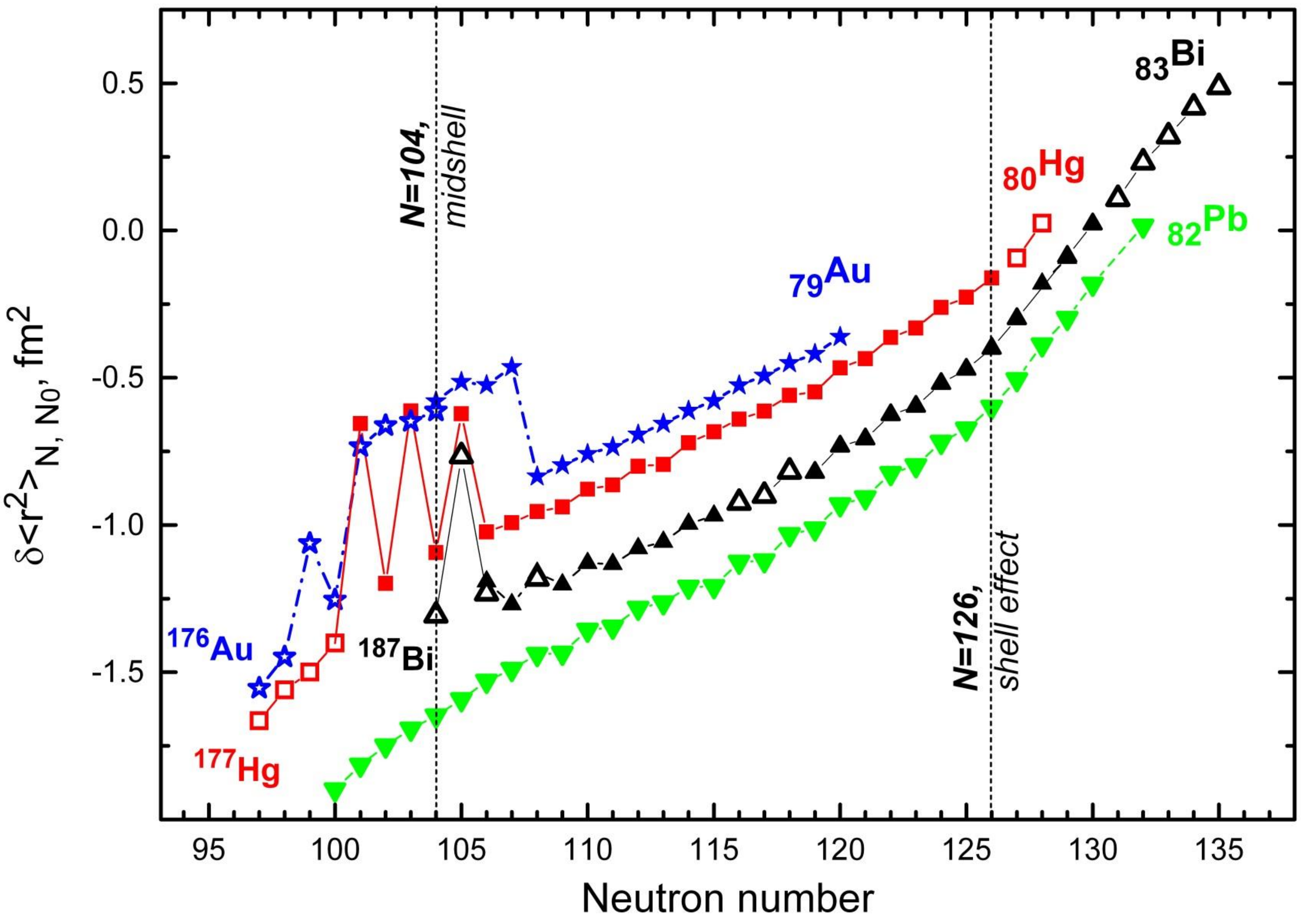
Relative Bi radii: Deviation from spherical trend (Pb)



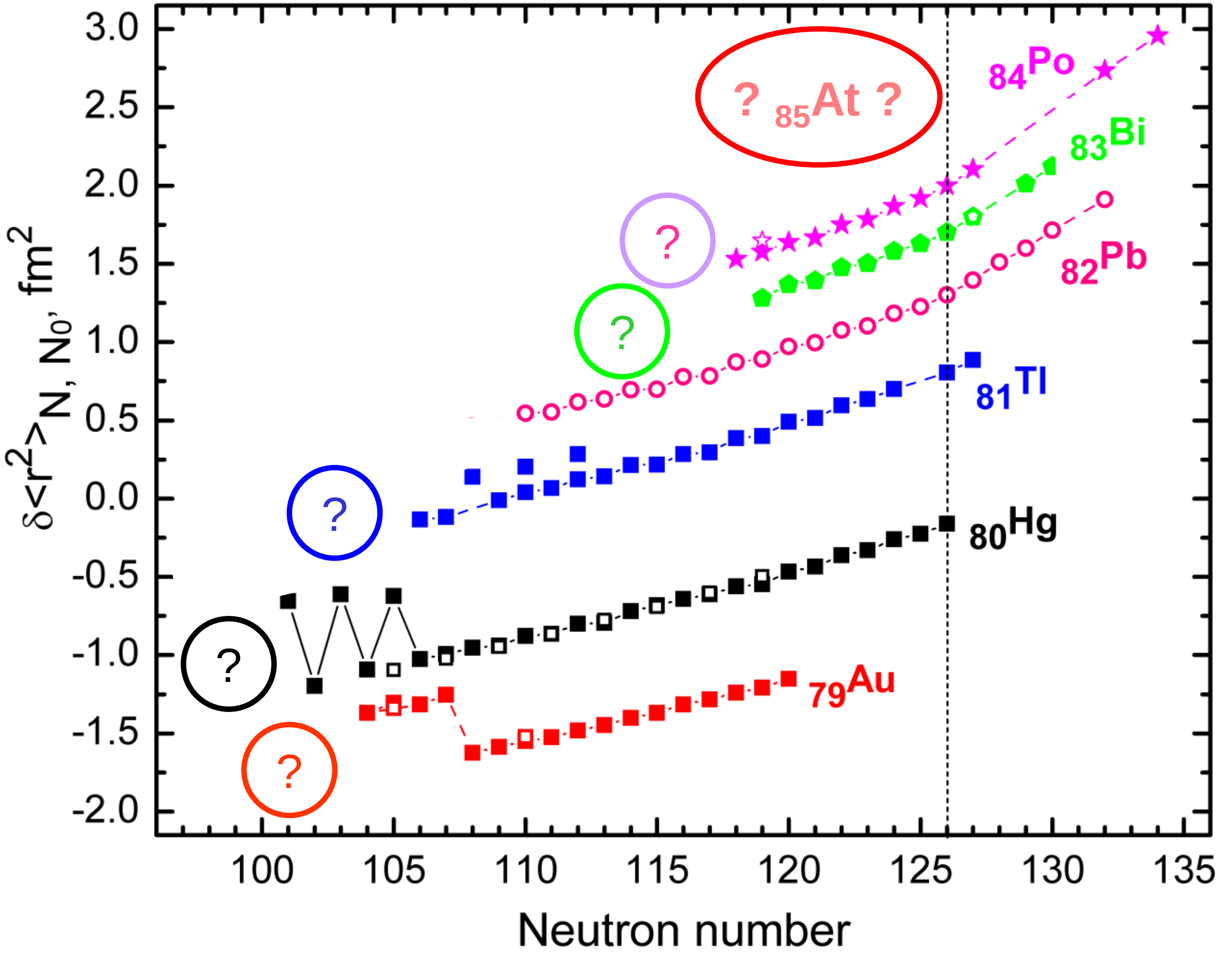
Marked deviation from the nearly spherical behavior for ground states of the even-neutron Bi isotopes at N < 111 in contrast to the Pb and Tl isotopic chains.
This deviation is interpreted as an indication of the onset of quadrupole deformation

The deviation from the Pb-radii trend for the odd-neutron Bi isotopes is smaller than that for the even-neutron Bi isotopes.
This leads to the pronounced odd-even effect at N < 111

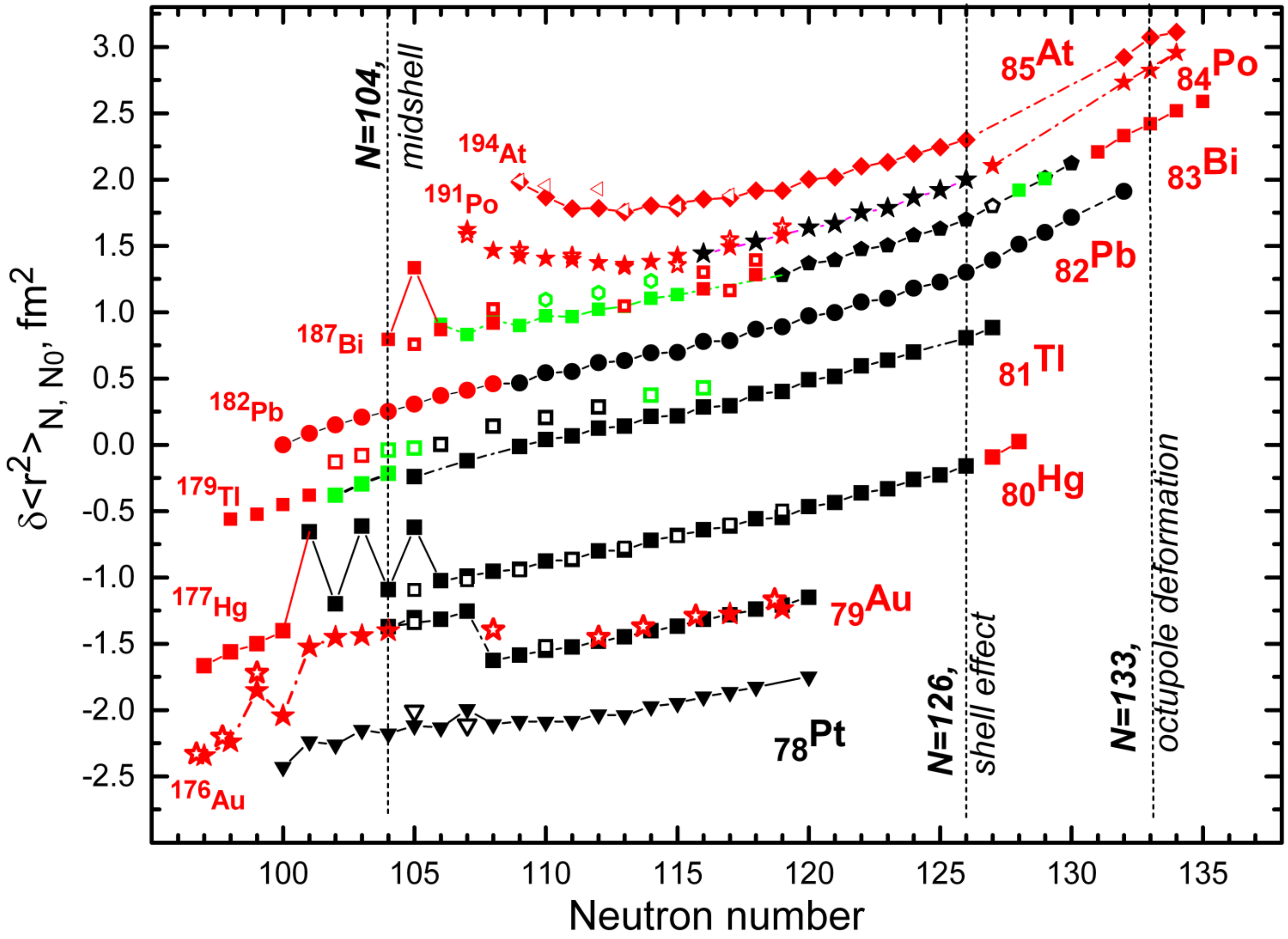
Radii in Pb-region: different shape evolution patterns



Charge radii in the lead region (2003)



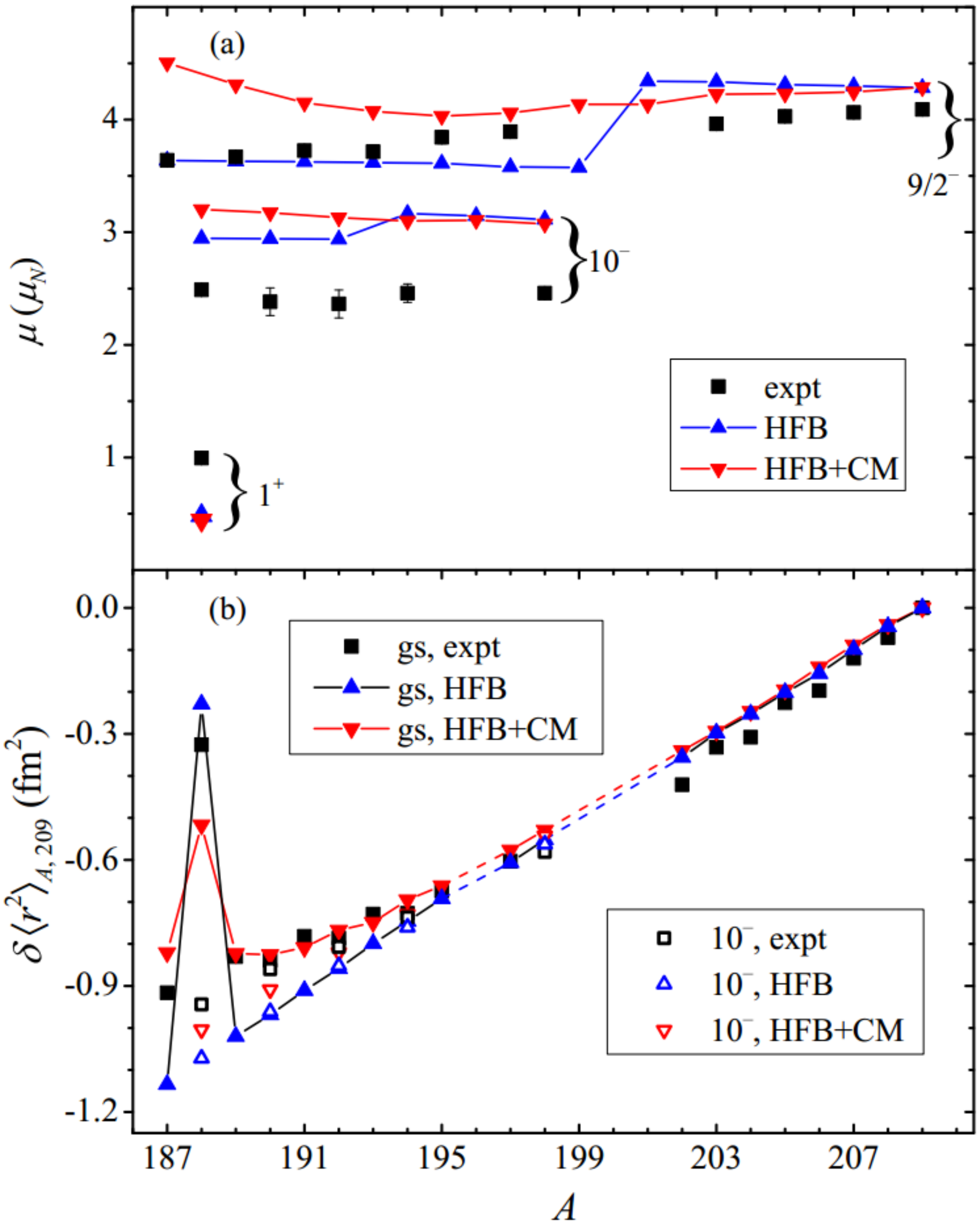
Charge radii in the lead region (2021)



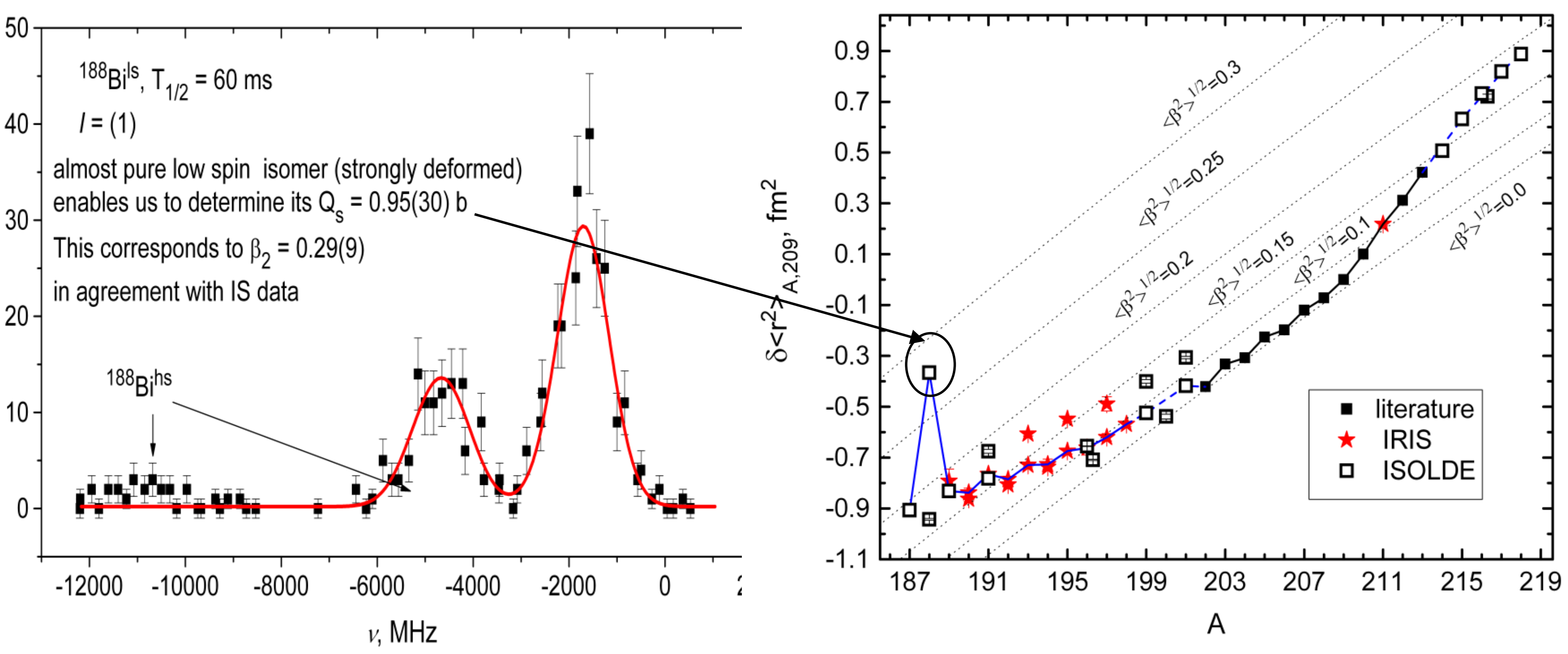
Conclusions

1. Laser ion source is very efficient tool for nuclear investigations due to its possibility to get the isobarically clean radioactive isotope beams of a great number of chemical elements.
2. Hyperfine structure parameters and isotope shifts of Bi isotopes relative to ^{209}Bi for the 306.9-nm atomic transition were measured using the in-source resonance-ionization spectroscopy technique at IRIS (PNPI) and ISOLDE (CERN). The changes in the mean-square charge radius, magnetic dipole and electric quadrupole moments were deduced using advanced atomic and molecular calculations.
3. A large staggering in radii was found near ^{188}Bi^{g}, along with the large isomer shift, at the same neutron number (N = 105), where the shape staggering starts and the similar isomer shift was observed in the mercury isotopes .
4. For the Bi nuclei the marked deviation from the isotopic trend of $\delta \langle r^2 \rangle$ in the lead isotopic chains has been demonstrated at $N < 111$. This deviation has been interpreted as an indication of the onset of quadrupole deformation.

Backup


(a)
$\mu\,(\mu_N)$
4
3
2
1
$9/2^-$
10^-
1^+
expt
HFB
HFB+CM
(b)
0.0
-0.3
-0.6
-0.9
-1.2
$\delta\langle r^2\rangle_{A,209}$ (fm^2)
gs, expt
gs, HFB
gs, HFB+CM
10^-, expt
10^-, HFB
10^-, HFB+CM
187
191
195
199
203
207
A

^{188}Bi: 2017 run



^{188}Bi^{ls}, $T_{1/2}$ = 60 ms

I = (1)

almost pure low spin isomer (strongly deformed) enables us to determine its Q_s = 0.95(30) b

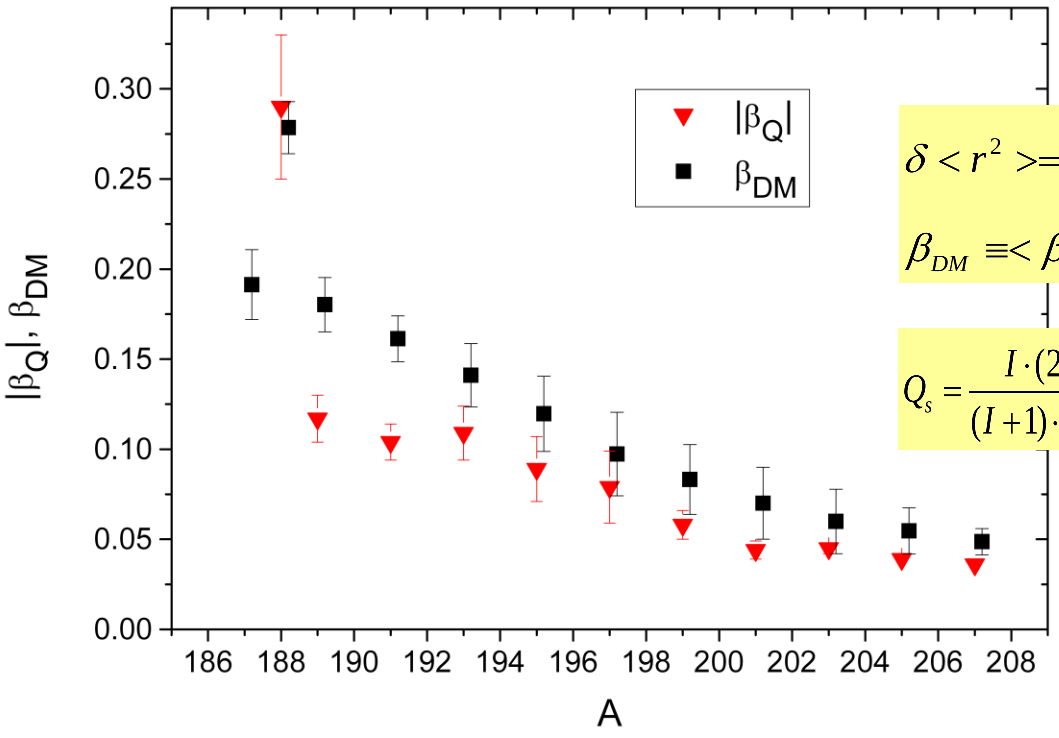
This corresponds to β_2 = 0.29(9)

in agreement with IS data

pure low spin isomer hfs due to better α-resolution

Thus, shape coexistence / shape staggering interpretation of the unusual and unexpected $\delta\langle r^2\rangle$ behavior is confirmed

Bi: deformation



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

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

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

Deformation parameter β_Q extracted from Q_s coincides with β from $\delta<r^2>$ and unambiguously testifies to the strong prolate deformation of $^{188}\mathrm{Bi}^{ls}$