Addendum to the IS608 Proposal

Shape-coexistence and shape-evolution studies for bismuth isotopes by in-source laser spectroscopy

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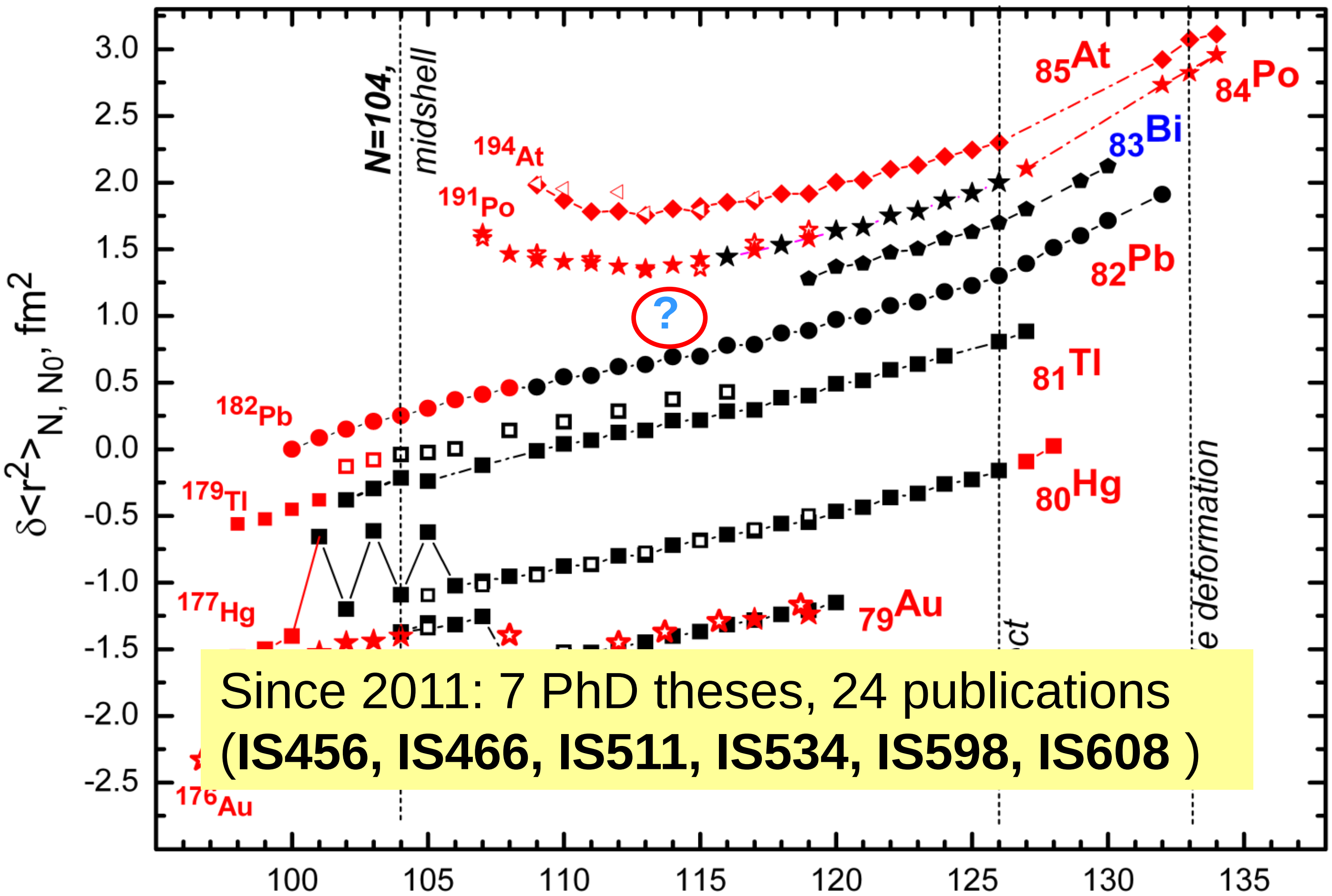
on behalf of Leuven-Gatchina-ISOLDE-Mainz-Manchester-York

and Windmill-ISOLTRAP-RILIS collaboration

Shape coexistence study in the Pb region

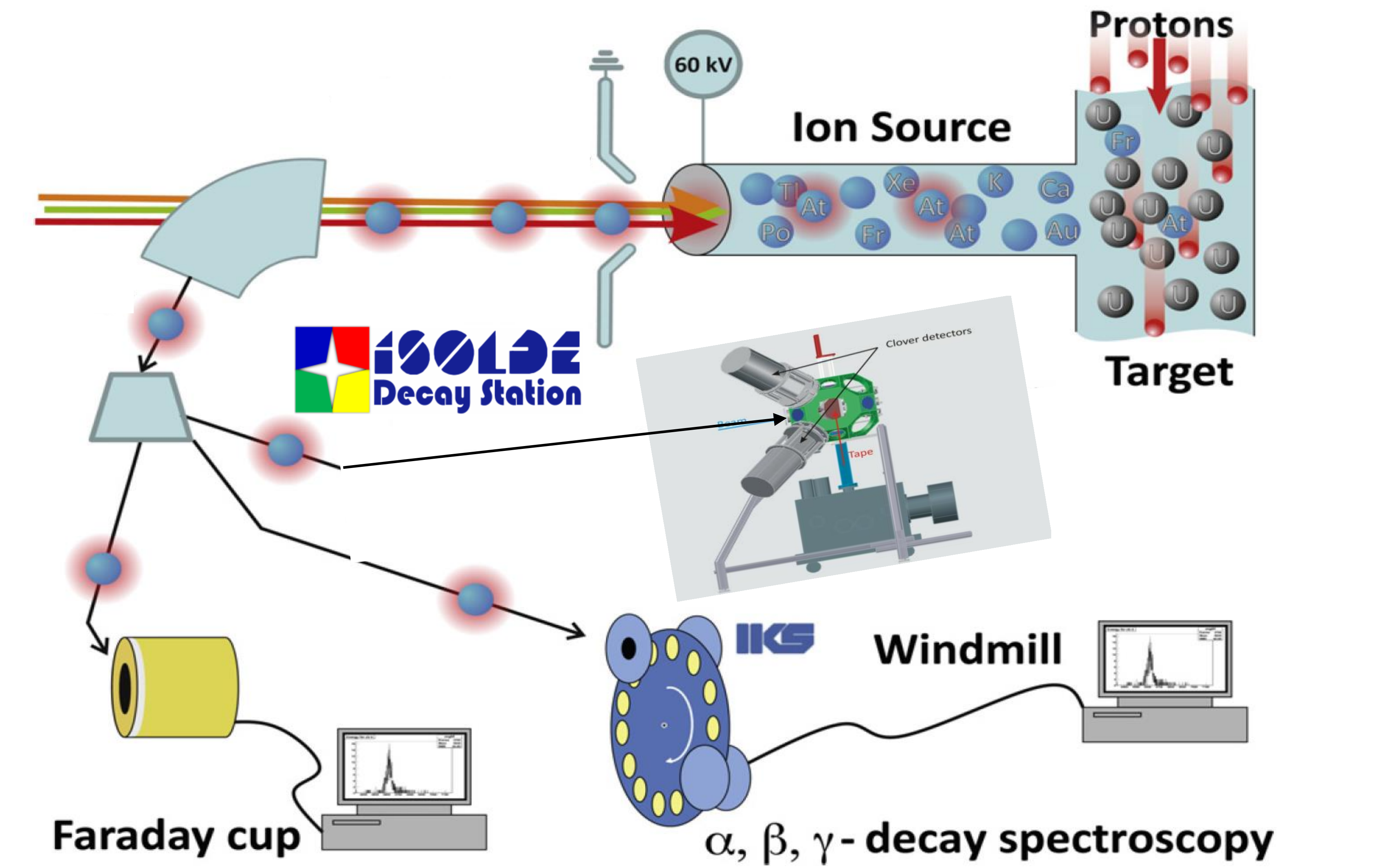
Windmill-RILIS-ISOLTRAP Collaboration



Since 2011: 7 PhD theses, 24 publications
(**IS456, IS466, IS511, IS534, IS598, IS608**)

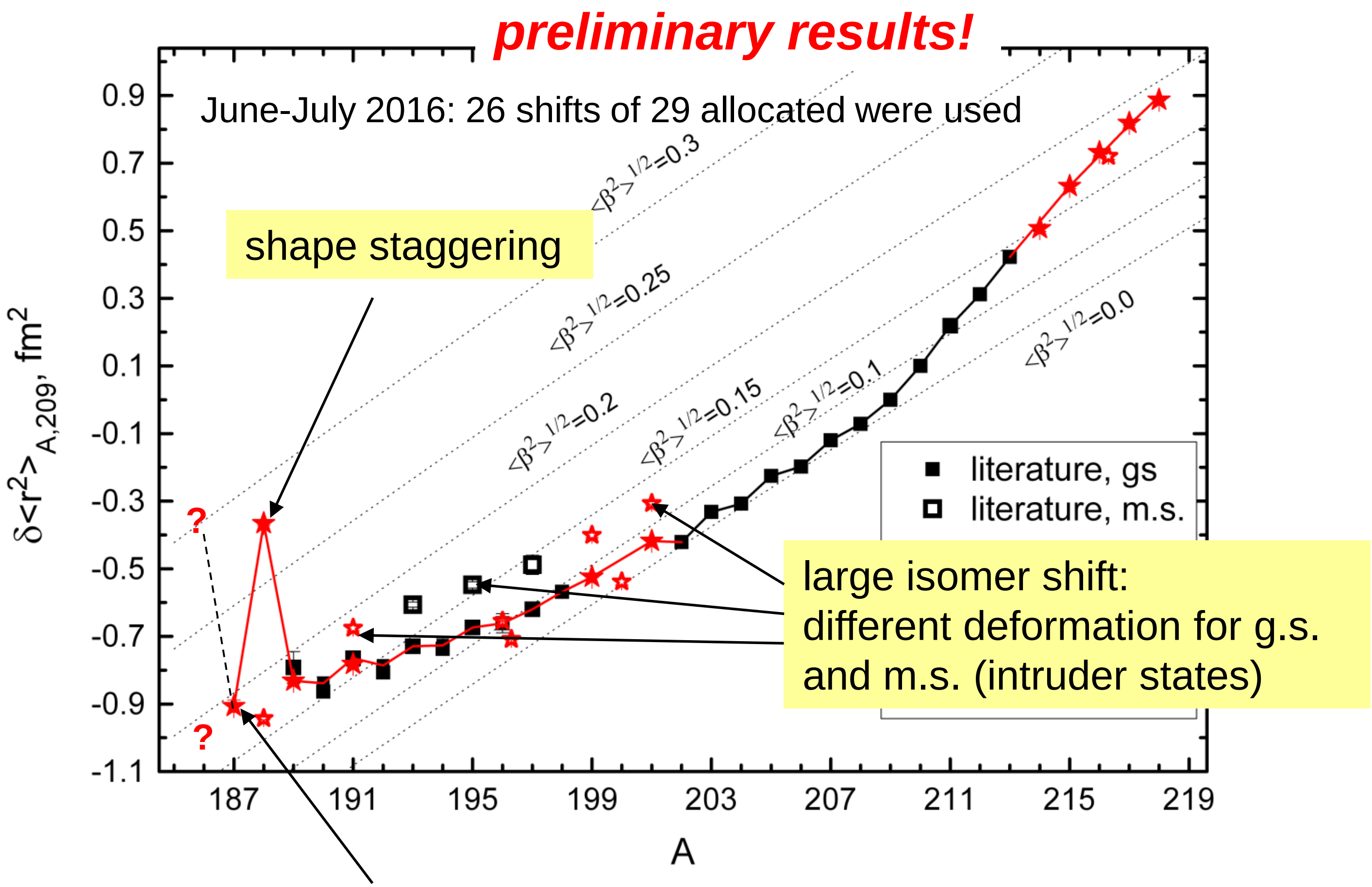
red points mark nuclei studied by our collaboration

ISOLDE: in-source spectroscopy



B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)
WM: A.N. Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)
MR-ToF MS: R. N. Wolf et al, NIM, A686, 82 (2012)

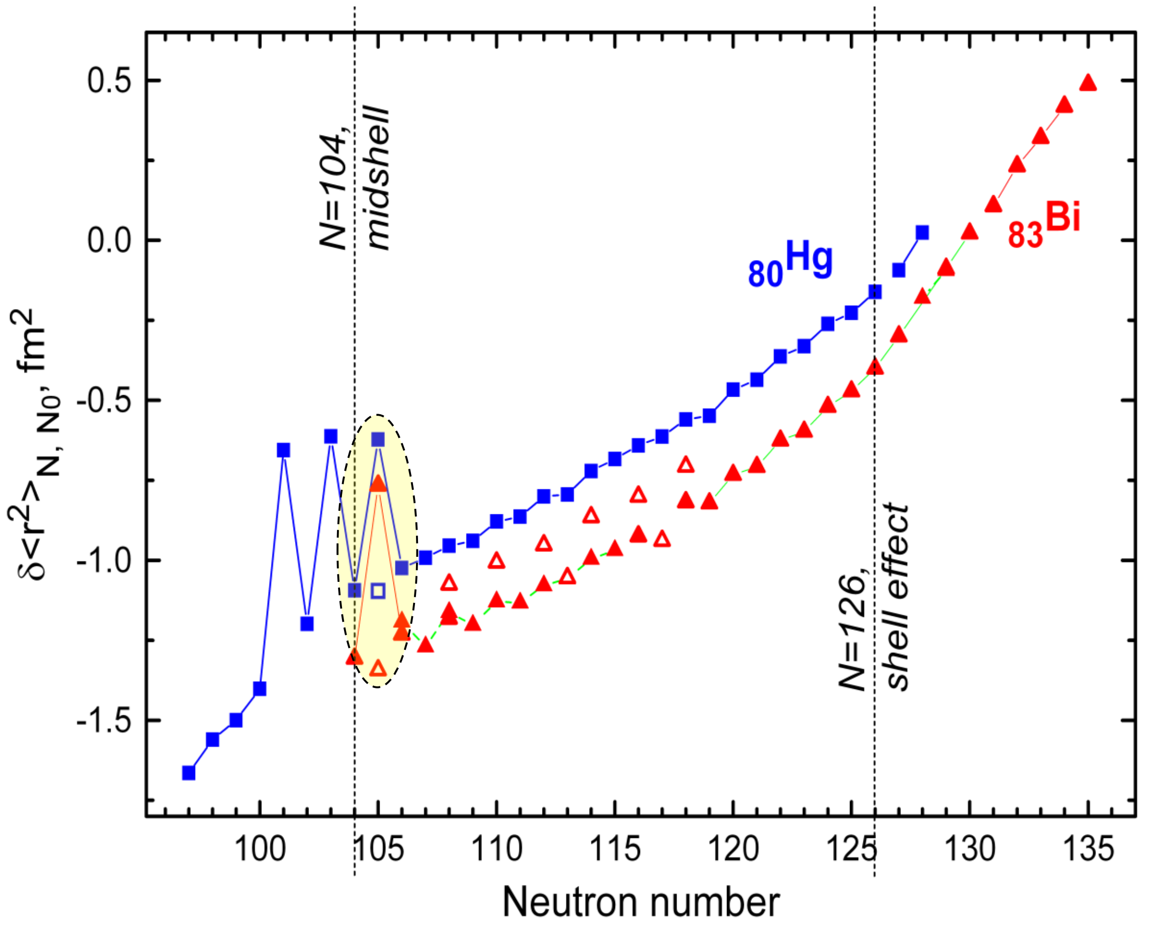
IS608, $_{83}$Bi isotopes: radii



^{187}Bi: $<\beta^2>^{1/2} = 0.18$

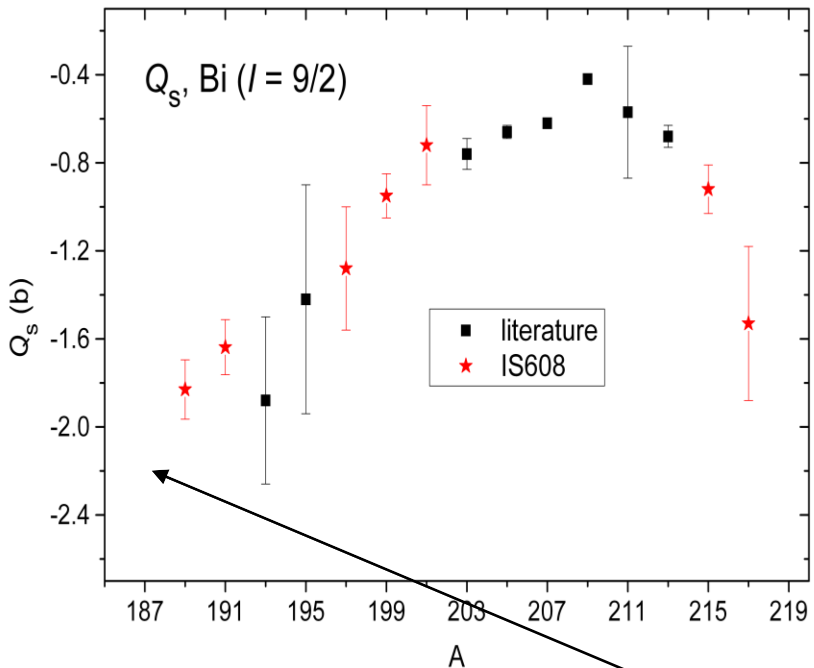
In contrast to previous conclusions on sphericity of the 9/2⁻ g.s for the light Bi isotopes, based on decay and in-beam studies, *a gradual onset of deformation in the 9/2⁻ gs of the lightest isotopes was deduced, up to $<\beta^2>^{1/2}$~0.18 in ^{187}Bi*

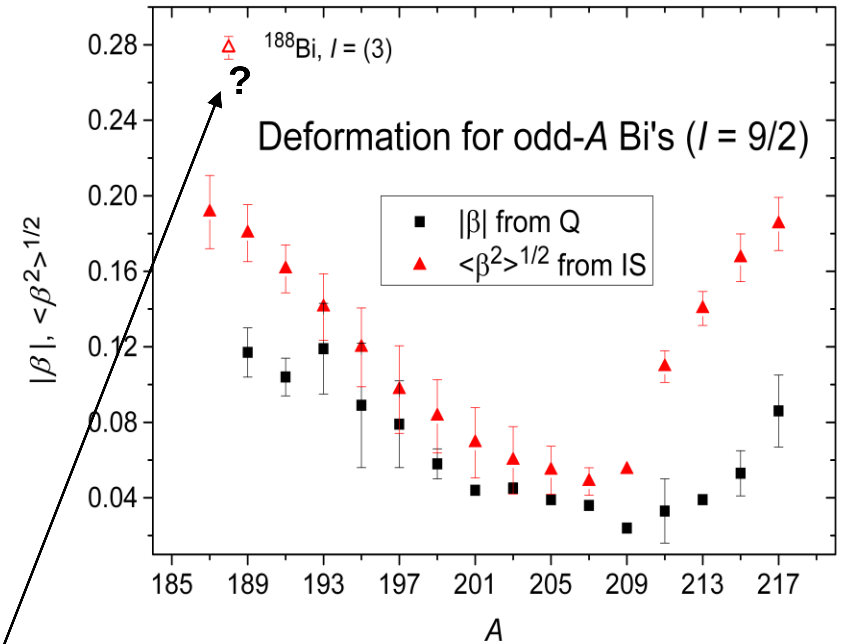
Hg and Bi radii



In Bi, shape staggering occurs at the same *N* as in Hg (*N* = 105), with the same amplitude and the same radii (deformation) difference between ground and $\nu i_{13/2}$ based isomeric states.

Bi quadrupole moments





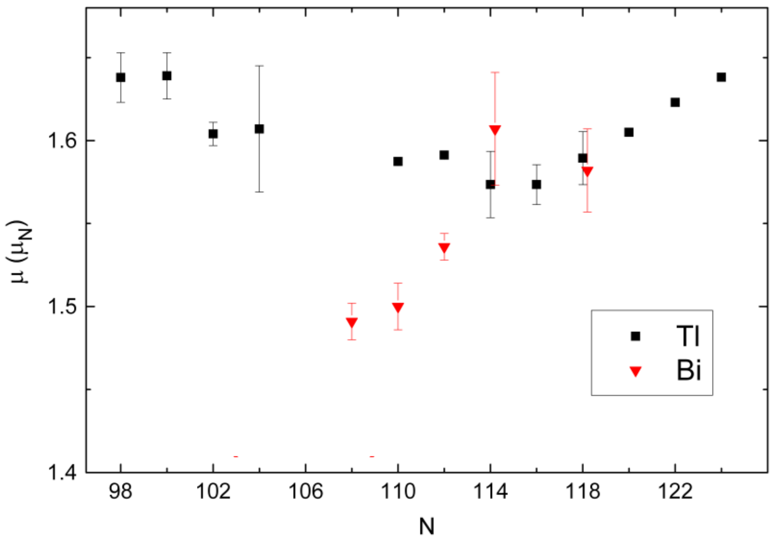
We propose to measure Q(^{188,187,193,195}Bi)

deformation for Bi and weak oblate deformation for Bi and Bi. Measurements of the quadrupole moments are needed to support this interpretation.

We also intend to decrease errors for Q in $^{193,\ 195}$Bi measured previously at IRIS(Gatchina).

We did not succeed in measuring the quadrupole moments for $^{187,\ 188m1,\ 188m2}$Bi nuclei due to power broadening. With a reduced laser power to avoid saturation, the duration of a laser scan should be increased by a factor of two.

Bi: intruders with $I^{\pi} = 1/2^{+}$



The μ($1/2^+$) for Bi intruder isomers starts to deviate from the “spherical” Tl trend at N<112.

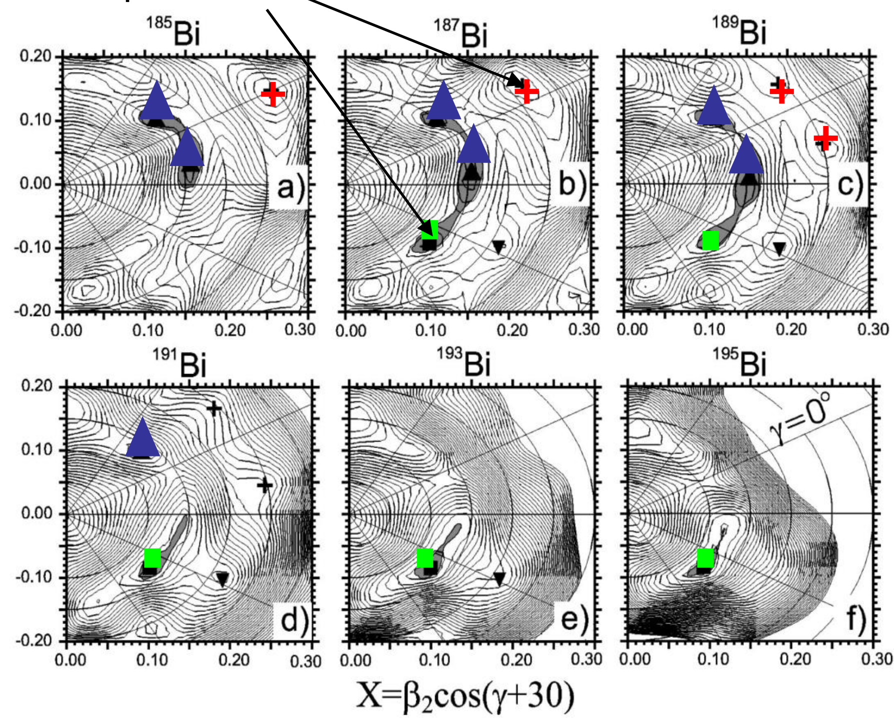
A measurement of $\mu(^{189}Bi^{m})$ would be crucial in supporting/rejecting this interpretation.

Positive parity states

'Oblate' intruders $I^{\pi}=1/2^{+}$

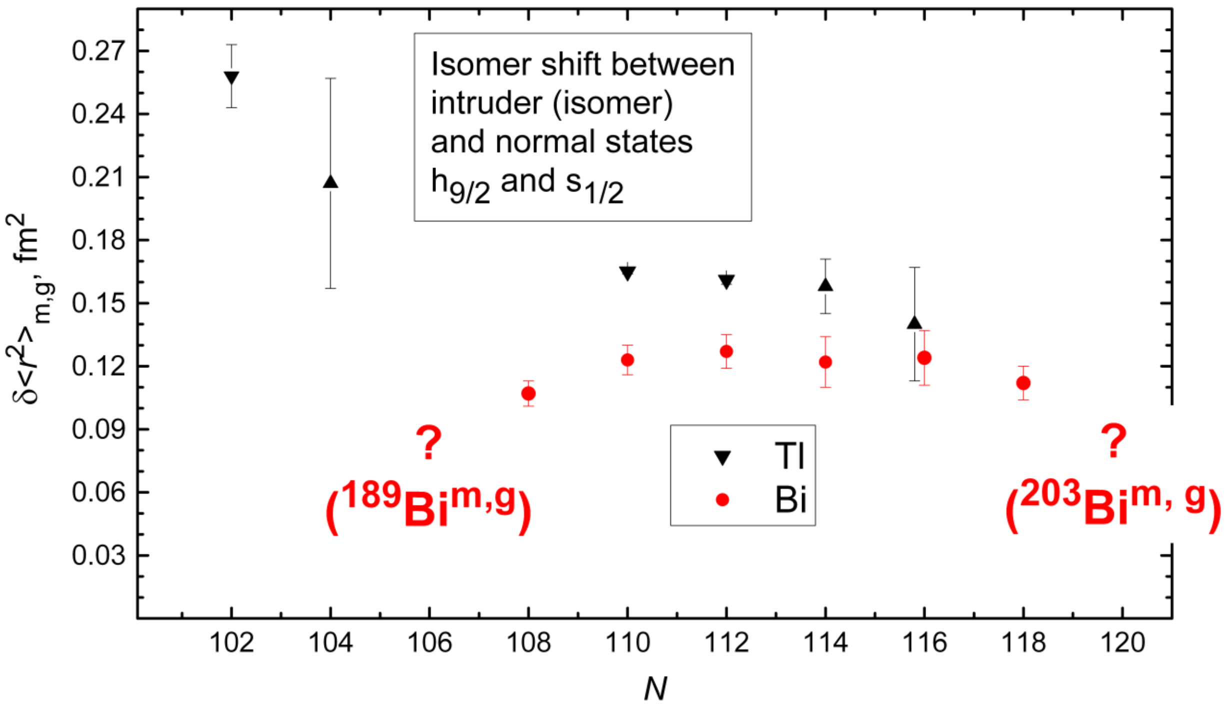
,+ 'Prolate' intruders $I^{\pi}=1/2^{+}$

two closely-spaced (oblate-prolate) $1/2^+$ states are predicted



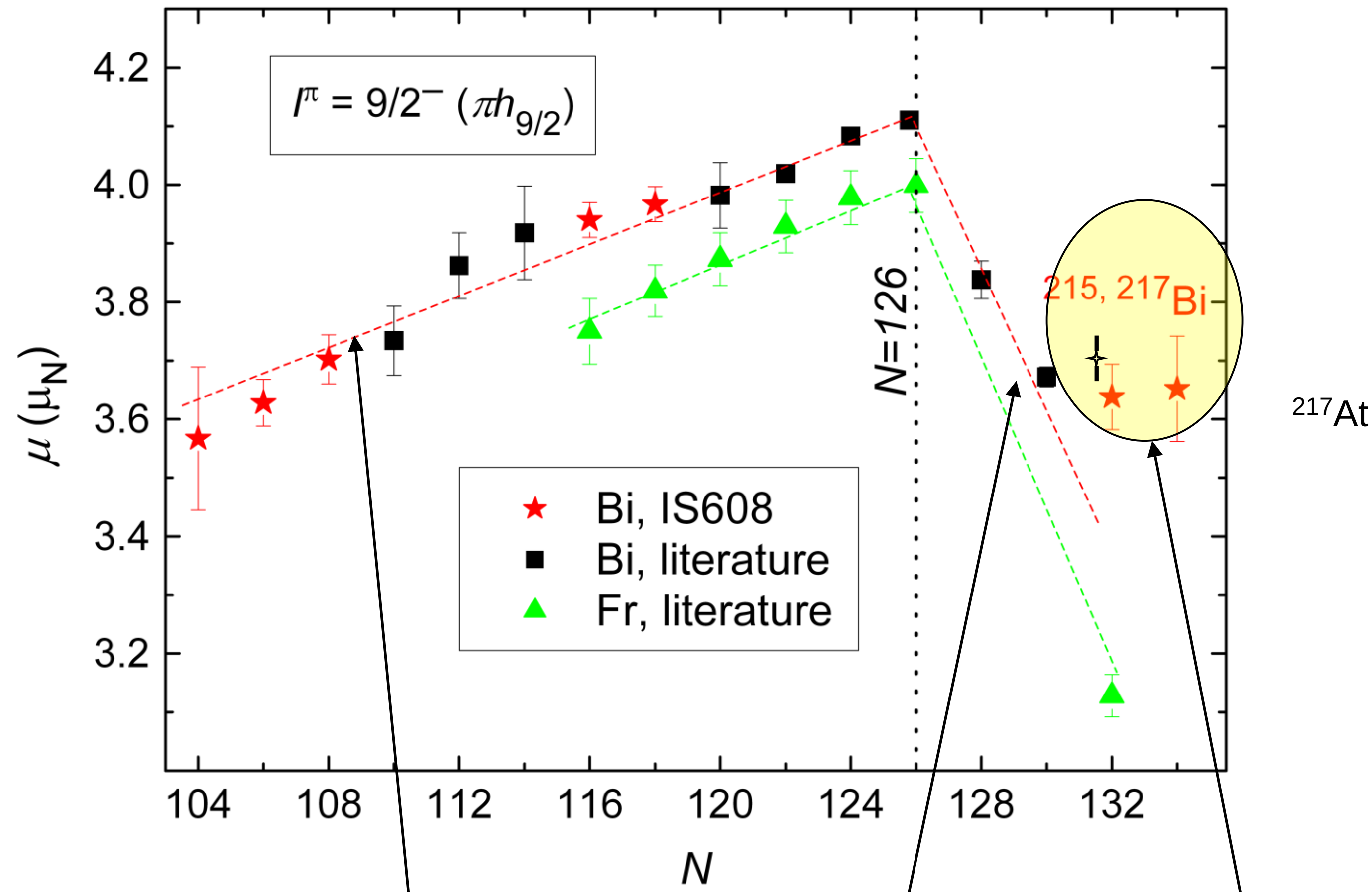
We propose to measure $\mu(^{189}Bi^{m})$

Bi: intruders with $I^{\pi} = 1/2^{+}$



We propose to measure $\delta\langle r^2\rangle$ for ^{189}Bi^{m}, ^{203}Bi^{m}

Bi: ground states μ ($I^{\pi} = 9/2^{-}$)



We propose to measure μ(^{219}Bi)

deviation from systematics: octupole degree of freedom influence?

odd-even staggering

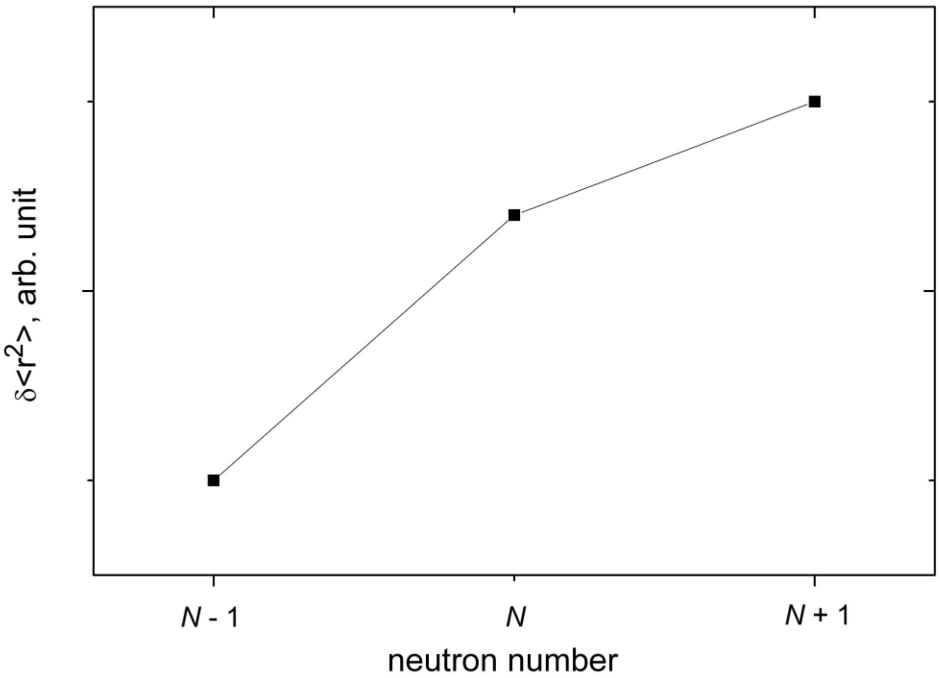
Octupole deformation correlates with the inverse radii staggering

staggering parameter: $\gamma(N) = \frac{2 \cdot \delta\left\langle r^2_{N,\,N-1} \right\rangle}{\delta\left\langle r^2_{N+1,\,N-1} \right\rangle}$ N — odd

$\gamma = 1$ — no staggering

$\gamma < 1$ — normal staggering

$\gamma > 1$ — inverse staggering



Bi: odd-even staggering

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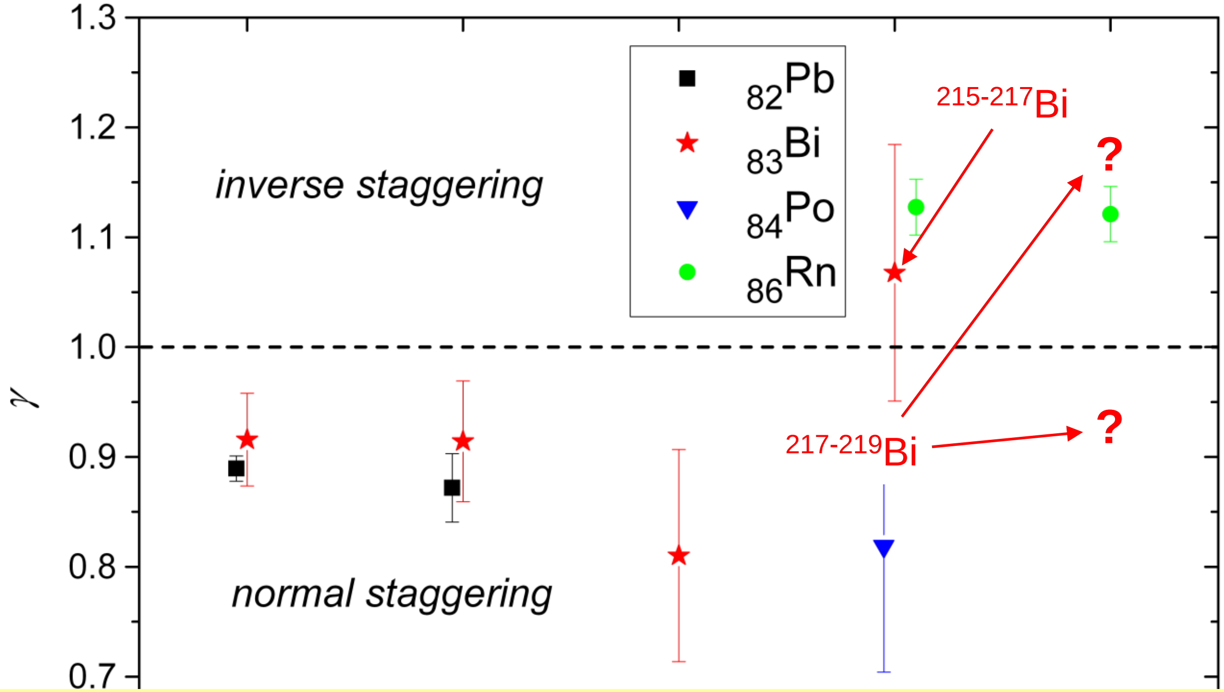


We propose to measure δ<r²>(^{219}Bi) → γ_{Bi}(135)

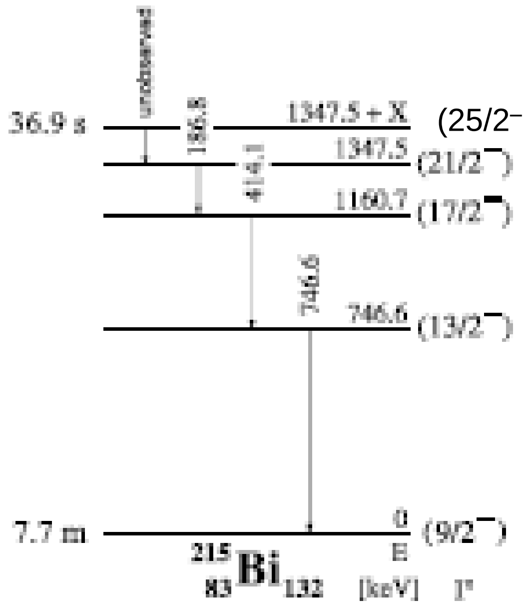
and to decrease error for γ_{Bi}(133)

Bi: high-spin isomers

$^{212}Bi^{m1}$ $(\pi h_{9/2}, \nu g_{9/2})_{8,9}$ 239(30) keV, **$^{212}Bi^{m2}$** $[\pi h_{9/2}, ((\nu g_{9/2})^2, \nu i_{11/2})]_{18}$ 1478(30) keV; L. Chen et al., PRL **110**, 122502 (2013) (Schottky Mass Spectrometry, GSI); unobserved IT branch of 75% is implied

$^{213}Bi^{m}$ $[\pi h_{9/2}, (\nu g_{9/2}, \nu i_{11/2})]_{25/2}$ 1353(21) keV; L. Chen et al., Nucl. Phys. A **882** (2012) 71 (Schottky Mass Spectrometry, GSI); $T_{1/2}$>168 s; intensive IT branch

We propose to measure $\delta\langle r^2\rangle$ (shell effect), μ (configuration) and Q for $^{212}Bi^{m1}$, $^{212}Bi^{m2}$, $^{213}Bi^{m}$, $^{214}Bi^{m}$, $^{215}Bi^{m}$ (with additional spectroscopic information: $T_{1/2}$, IT decay etc)



According to the Hartree-Fock calculations the value of shell effect in radii is critically dependent on the occupancy of the neutron $\nu i_{11/2}$ shell which is markedly changed for these high-spin isomers.

P. M. Goddard, P. D. Stevenson, and A. Rios. PRL, **110**, 032503, 2013

Total beam request

A	I	$T_{1/2}$, s	Yield, 1/μC	Method of measurement	time, shifts
219	(9/2)	22	$>3\times10^{1}$	IDS	1.5
217	(9/2)	98.5	$>3\times10^{2}$	IDS	0.5
215m	(29/2– 25/2)	36.9	$>1\times10^{3}$	IDS	1
214m	?	>93	$>1\times10^{3}$	IDS	1
213m	(25/2)	>168	$>1\times10^{3}$	IDS	1
212m1	(18)	420	$>1\times10^{3}$	IDS	1
212m2	(8,9)	1500	$>1\times10^{3}$	IDS	1
203m	1/2	0.305	1.9×10^{6}	IDS	0.5
195	(9/2)	183	1.4×10^{7}	IDS	0.5
193	(9/2)	63.6	3×10^{6}	IDS	0.5
189m	(1/2)	0.005	1	WM	2.5
188m1 188m2	(3)	0.06	20	WM	1.5
	(10)	0.265	10^{2}	WM	
187g	(9/2)	0.037	0.3	WM	2.5

Yields were estimated using the observed during the IS608 run count rates with the known/extrapolated isomer ratios.

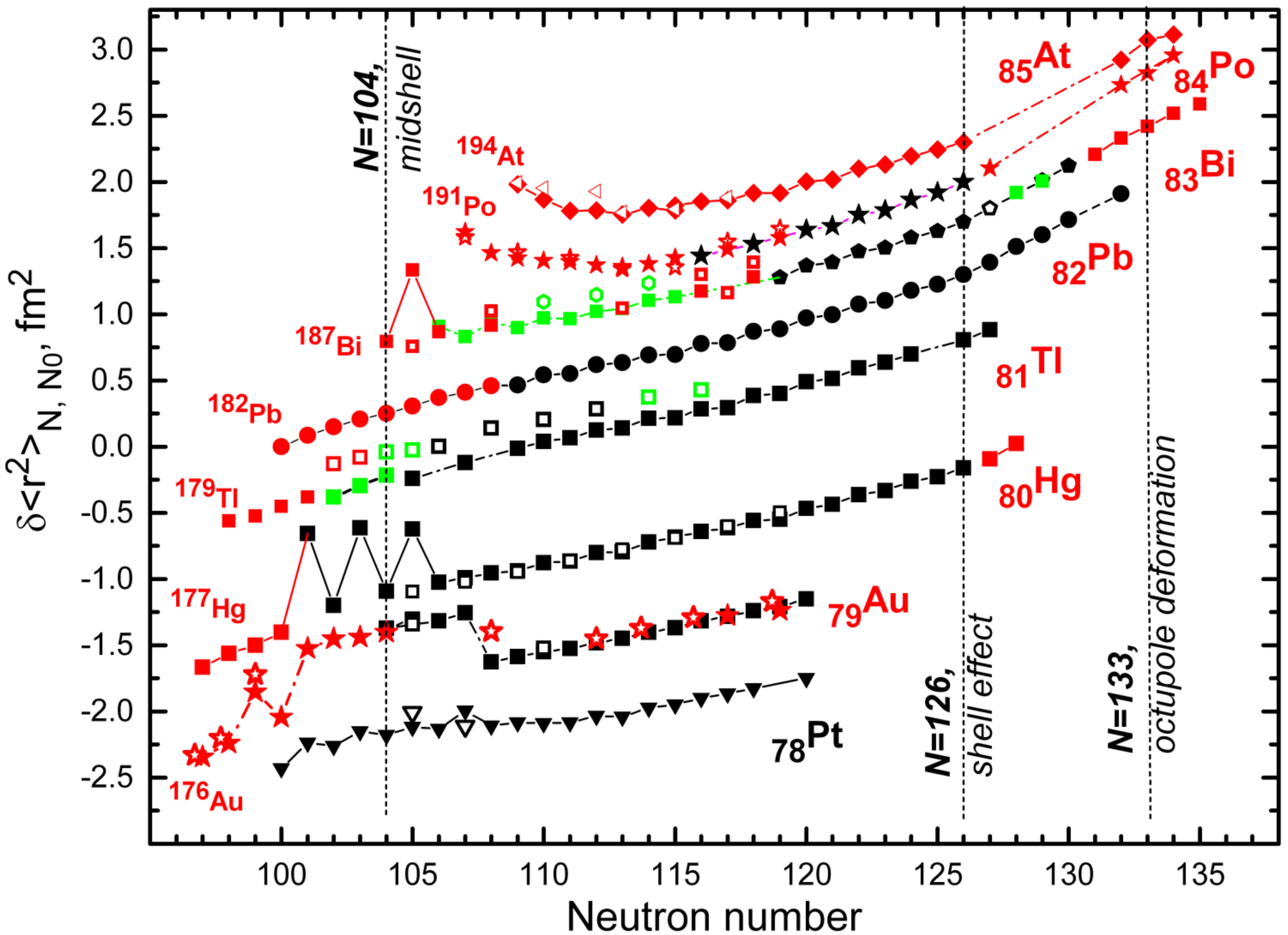
Thallium contaminats for A = 187-191 were not a problem during the IS608 run.

Measurements for A = 203 are planned at IDS by IT gamma transition monitoring. Thus, stable ^{203}Tl will not disturb these measurements.

^{214}Ra and daughter ^{210}Rn have weak beta-decay branches (0.06% and 4%). The overall contaminant gamma intensity will not exceed 10^{3} 1/s which is comparable with the expected Bi gamma lines intensity (IDS).

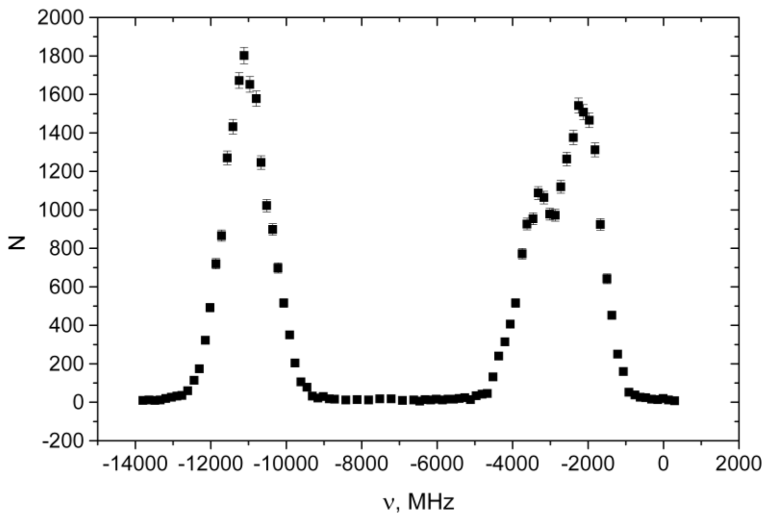
In total, 16 Shifts are requested for Bi IS/hfs studies. By accounting for 3 remaining shifts from IS608, the present beam-time request is 13 shifts

Shape coexistence study in the Pb region



$^{189}Bi^{m}$

$^{189}Bi^{g}$

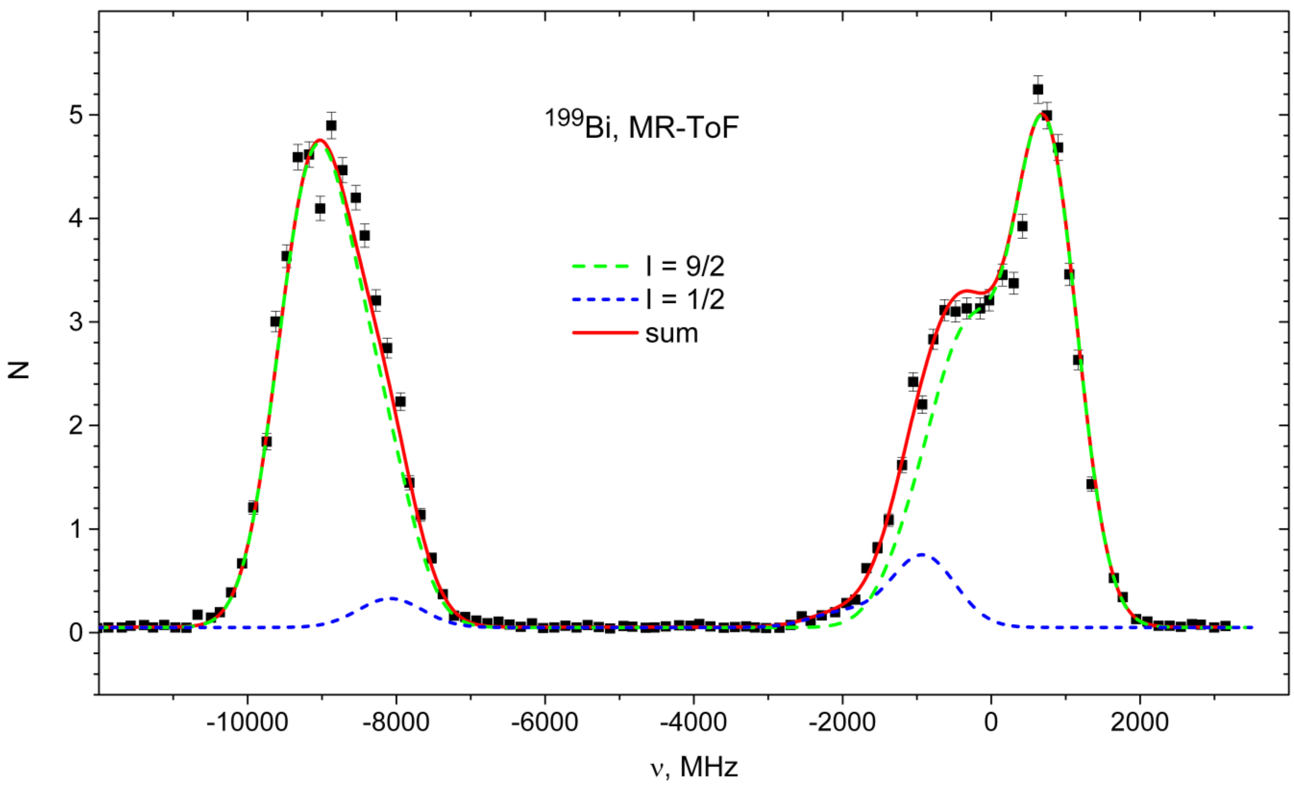


The similar estimation for $^{191g,\ 191m}Bi$ was checked during the IS608 run

$^{189}Bi^{g}$: $T_{1/2}$=658 ms, t_{coll}=1 SC, I_{max} ($^{189}Bi^{g}$) =1800

$^{189}Bi^{m}$: $T_{1/2}$=5 ms, isomer ratio R ~ 6,
relative decay losses L ~ ($T_{1/2}$($^{189}Bi^{g}$)/$T_{1/2}$($^{189}Bi^{m}$) = 130
t_{coll} = 9 SC
I_{max} ($^{189}Bi^{m}$) = I_{max} ($^{189}Bi^{g}$) / R / L*t_{coll} = 20
60 points ~ 7 hours

Isomers: MR-ToF vs IDS

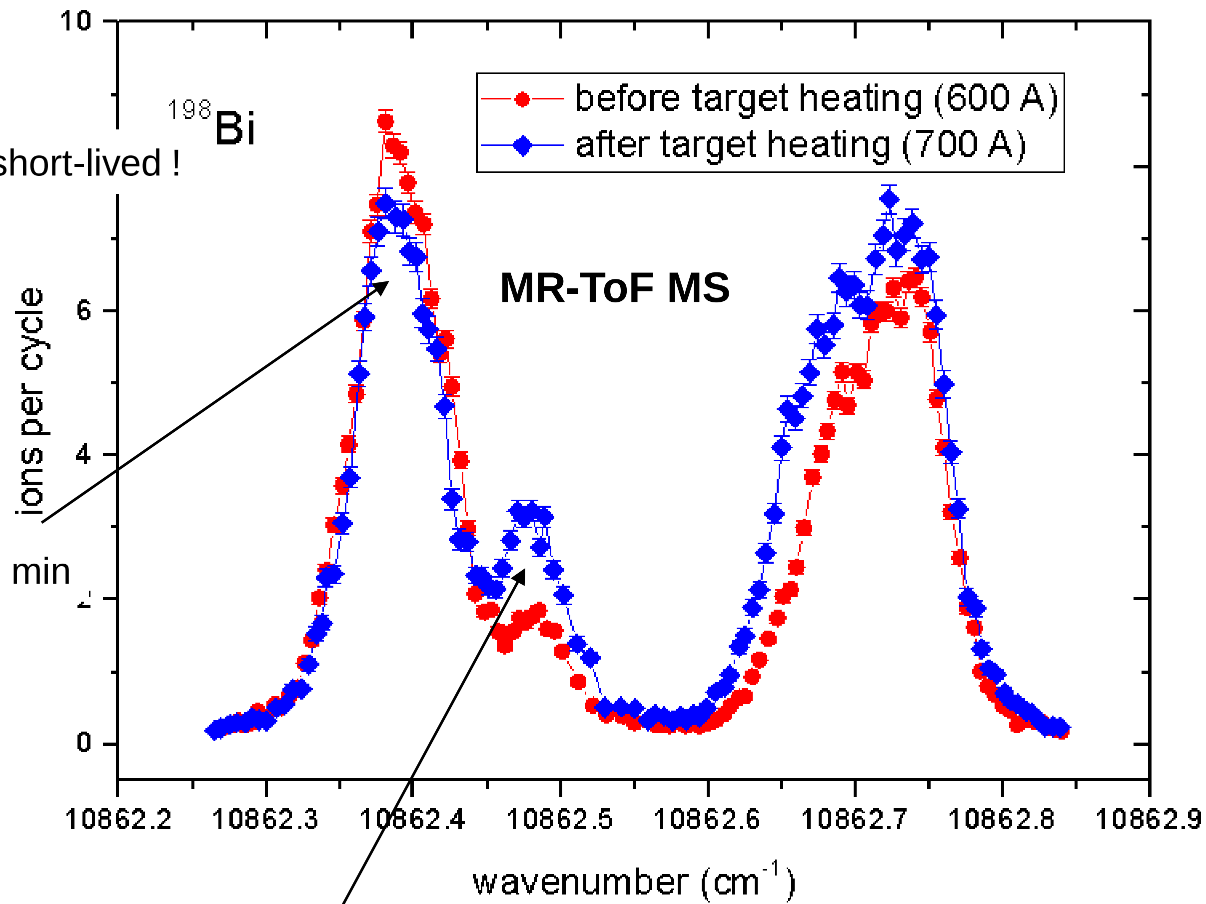


In MR-ToF mode the isomer hfs is buried under the gs hfs.
Keeping in mind small isomer ratio (~0.1) it is preferable to use IT transitions at IDS to obtain pure isomer hfs

Target temperature

1940° ⇨ 2200°

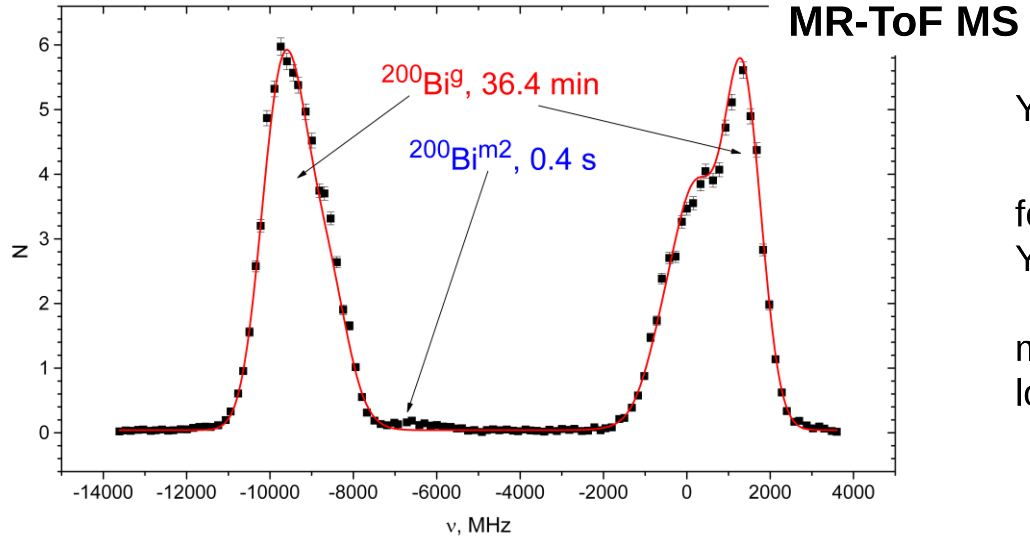
3 times increase for the short-lived !



$^{198}Bi^{m1}$, I = 7, $T_{1/2}$ = 11.6 min

$^{198}Bi^{m2}$, I = 10, $T_{1/2}$ = 7.7 s

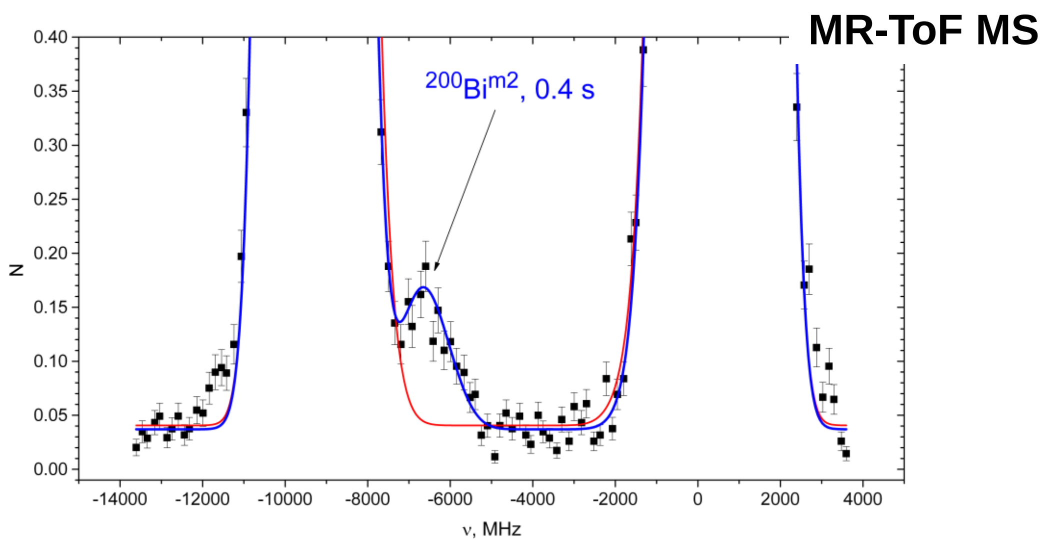
Target temperature



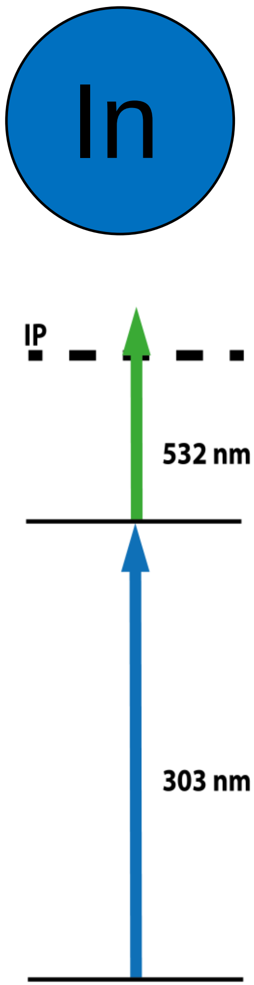
$Y(^{200}Bi^{g}) / Y(^{200}Bi^{m2}) = 40$

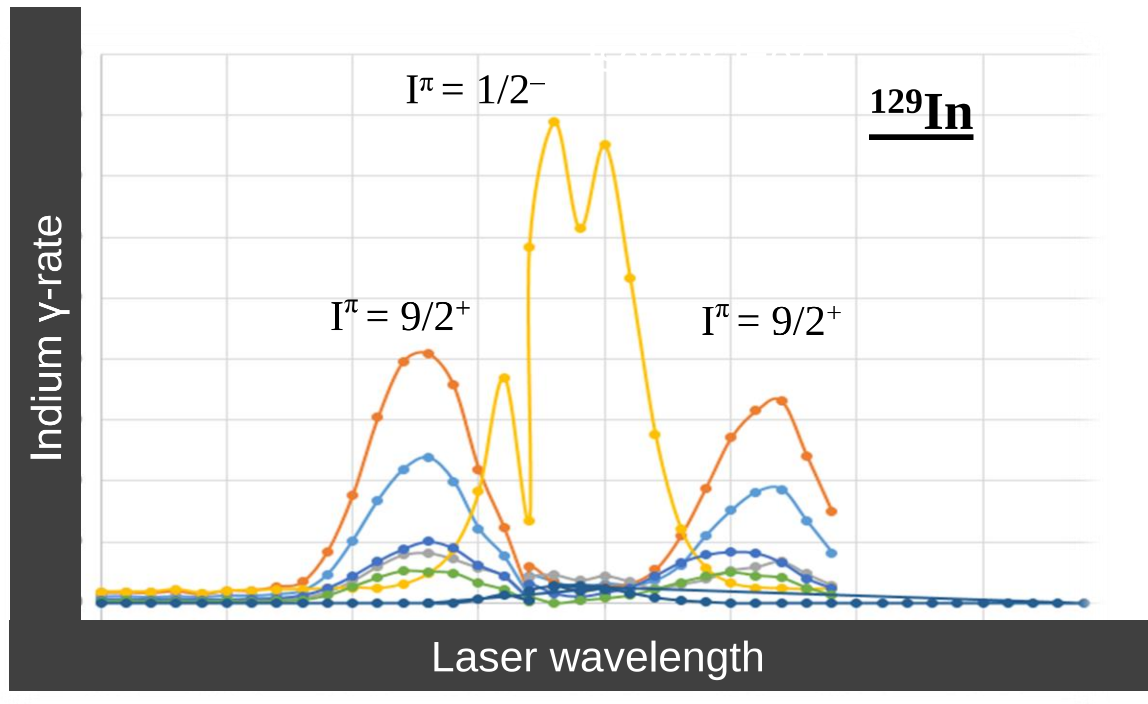
for completely similar ^{198}BI:
$Y(^{198}Bi^{g}) / Y(^{198}Bi^{m2}) = 4$

more than order of magnitude decay losses due to low target temperature!



First RILIS-IDS hfs scan

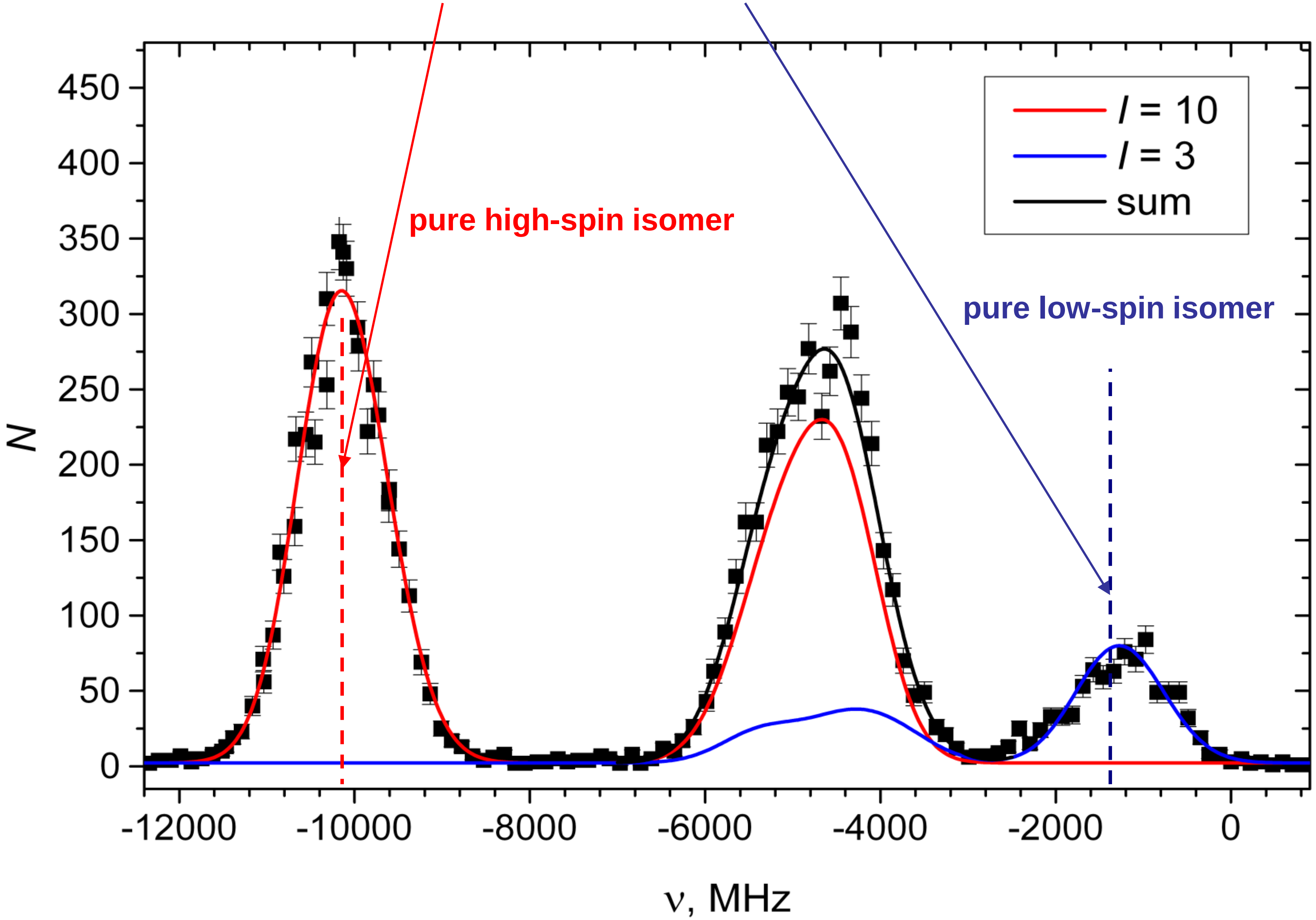




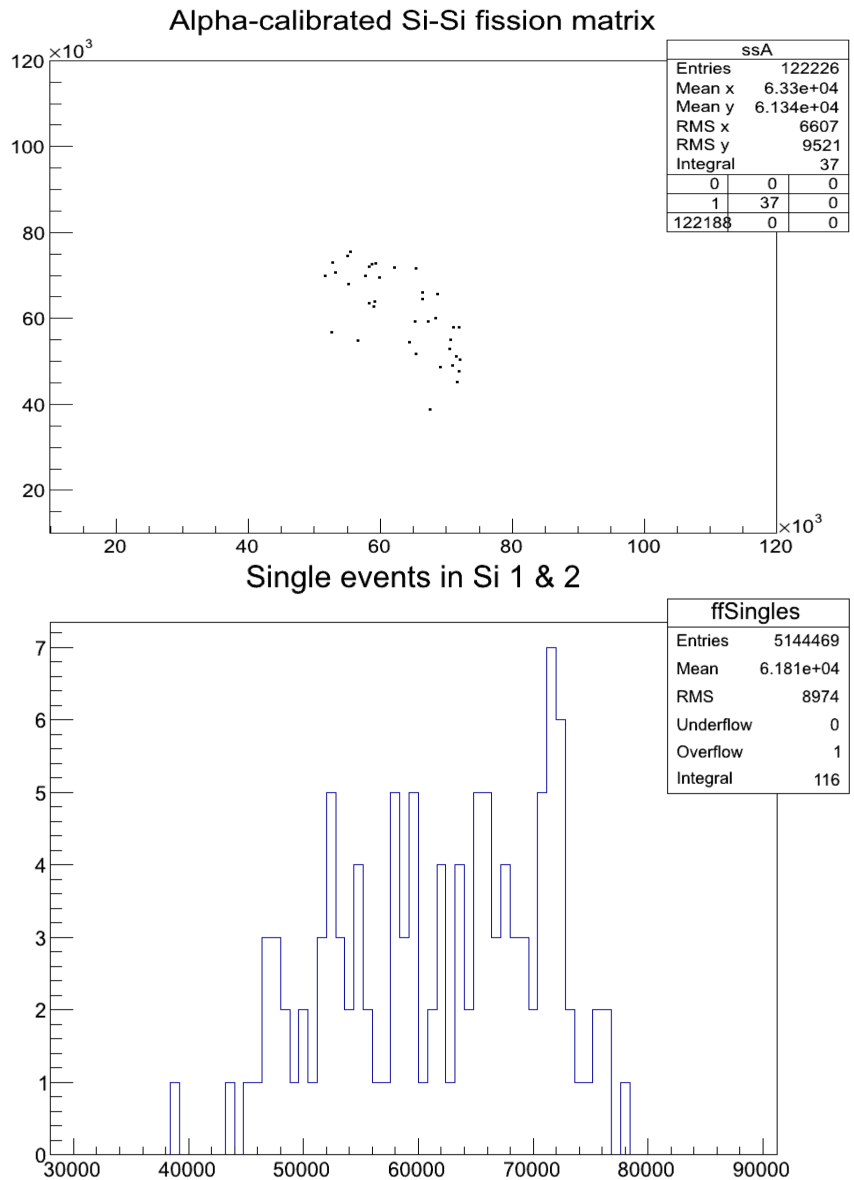
courtesy by T. D. Goodacre

^{188}Bi: Isomer selective beta delayed fission

at these frequencies we obtain at the exit of the mass-separator…



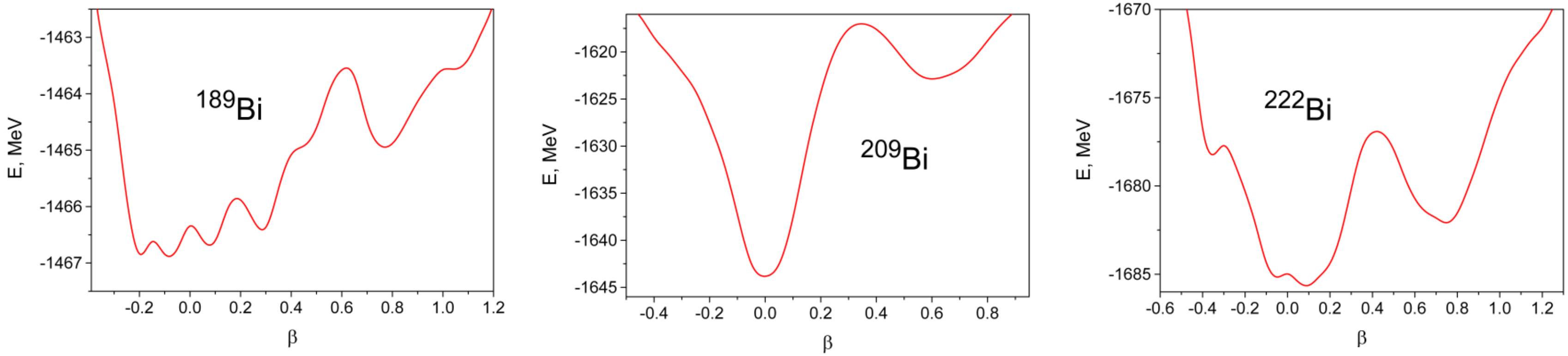
^{188}Bi: Isomer selective beta delayed fission



$P_{bDF}(^{188}Bi, I = 10) = 6.0(1.7)\cdot10^{-4}$

Fission fragment mass distribution is similar to that for ^{196}At where multimodal fission was found.

A reminder on the underlying physics phenomena



Potential energy curves for $^{189,\ 209,\ 222}$Bi calculated in HFB approach with Gogny forces D1S

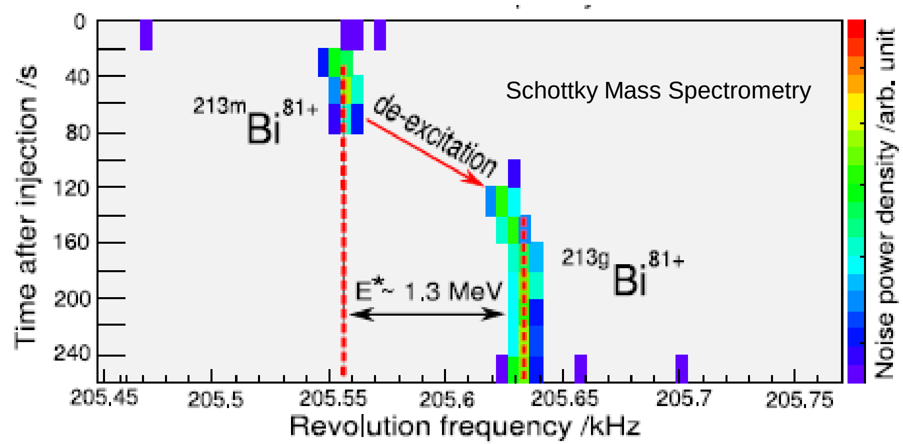
A gradual transition to deformed configurations is expected when moving towards either neutron-deficient or neutron-rich Bi isotopes

Many-minima picture was obtained for the $^{187,\ 188}$Bi, where the competition of at least four minima at oblate/prolate sides takes place.

S. Hilaire, M. Girod, Hartree-Fock-Bogoliubov results based on the Gogny force, http://www-phynu.cea.fr/science_en_ligne/carte_potentiels_microscopiques

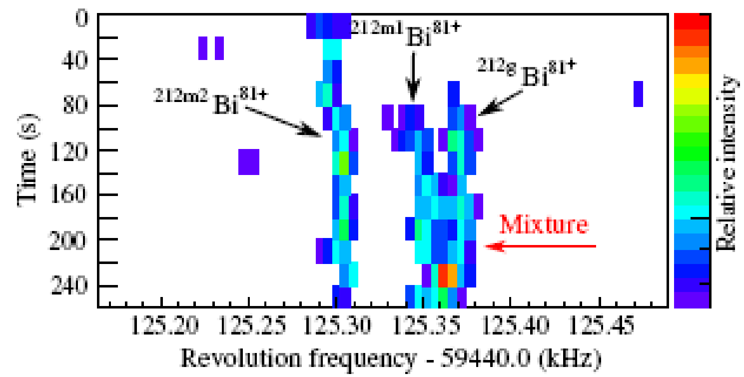
Bi: high-spin isomers

$^{213}Bi^{m}$ $[\pi h_{9/2}, (\nu g_{9/2}, \nu i_{11/2})]_{25/2}$

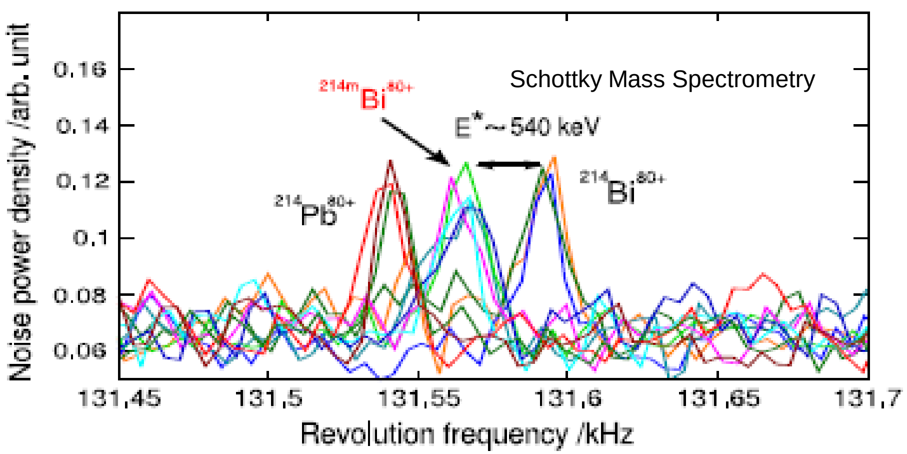


L. Chen et al., Nucl. Phys. A 882 (2012) 71
$T_{1/2}$>168 s; intensive IT branch

$^{212}Bi^{m1}$ $(\pi h_{9/2}, \nu g_{9/2})_{8,9}$, $^{212}Bi^{m2}$ $[\pi h_{9/2}, ((\nu g_{9/2})^2, \nu i_{11/2})]_{18}$

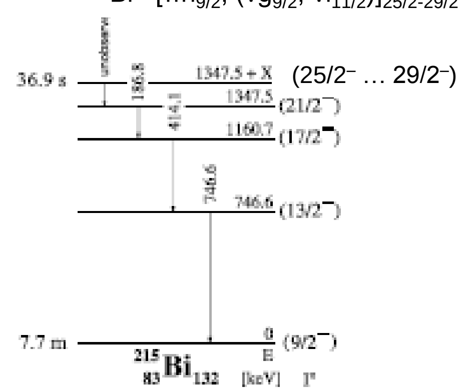


L. Chen et al., PRL 110, 122502 (2013);
unobserved IT branch of 75% is implied



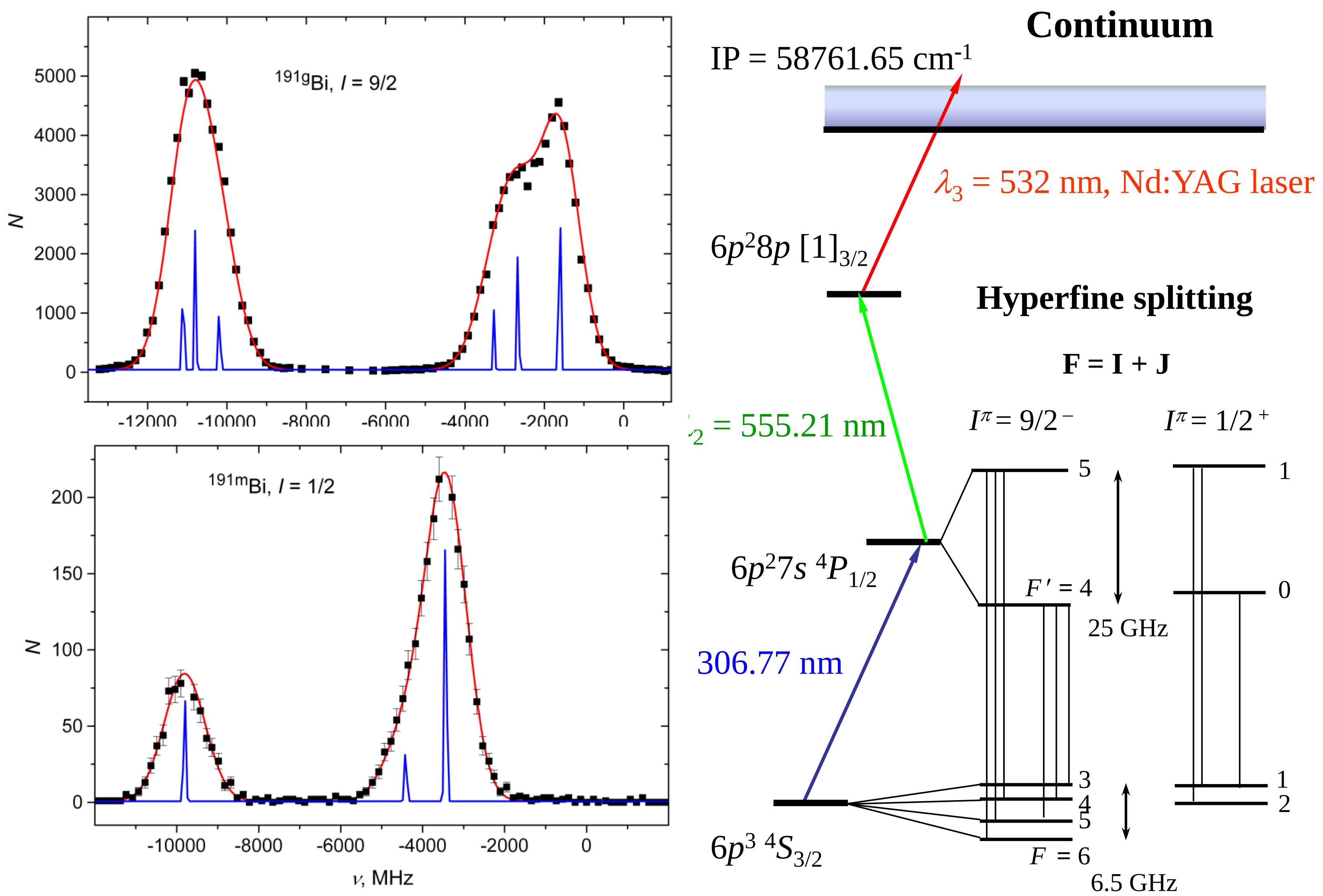
$T_{1/2}$>93 s

$^{215}Bi^{m}$ $[\pi h_{9/2}, (\nu g_{9/2}, \nu i_{11/2})]_{25/2-29/2}$



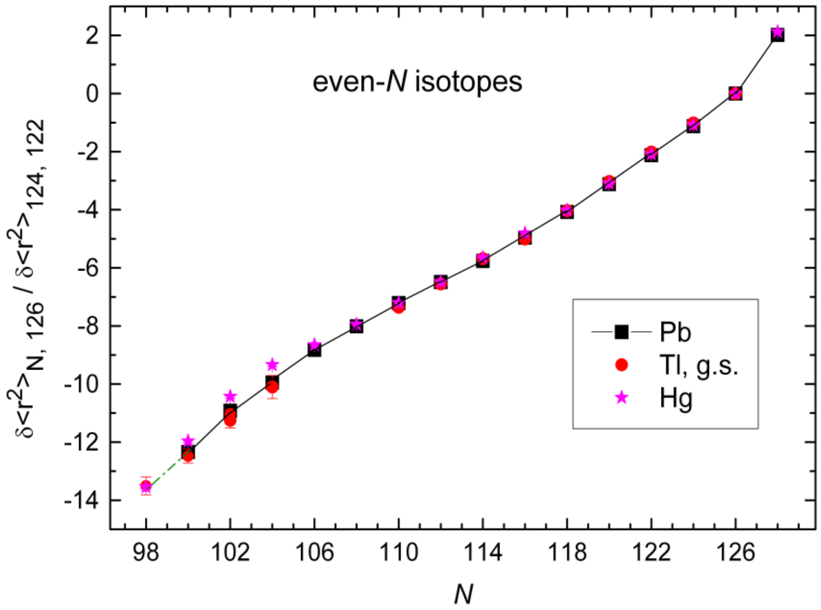
J. Kurpeta et al., Eur. Phys. J. A **18**, 31 (2003)

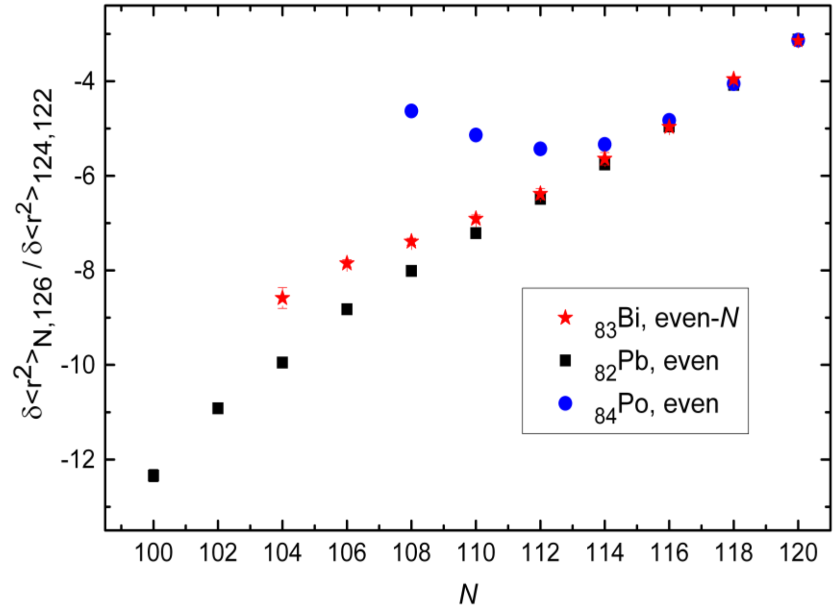
Bi: hfs spectra



Bi: relative radii

For comparison of radii trends for different isotopic chains it is better to use relative $\delta\langle r^2\rangle$: $\delta\langle r^2\rangle_{N,126} / \delta\langle r^2\rangle_{124,122}$



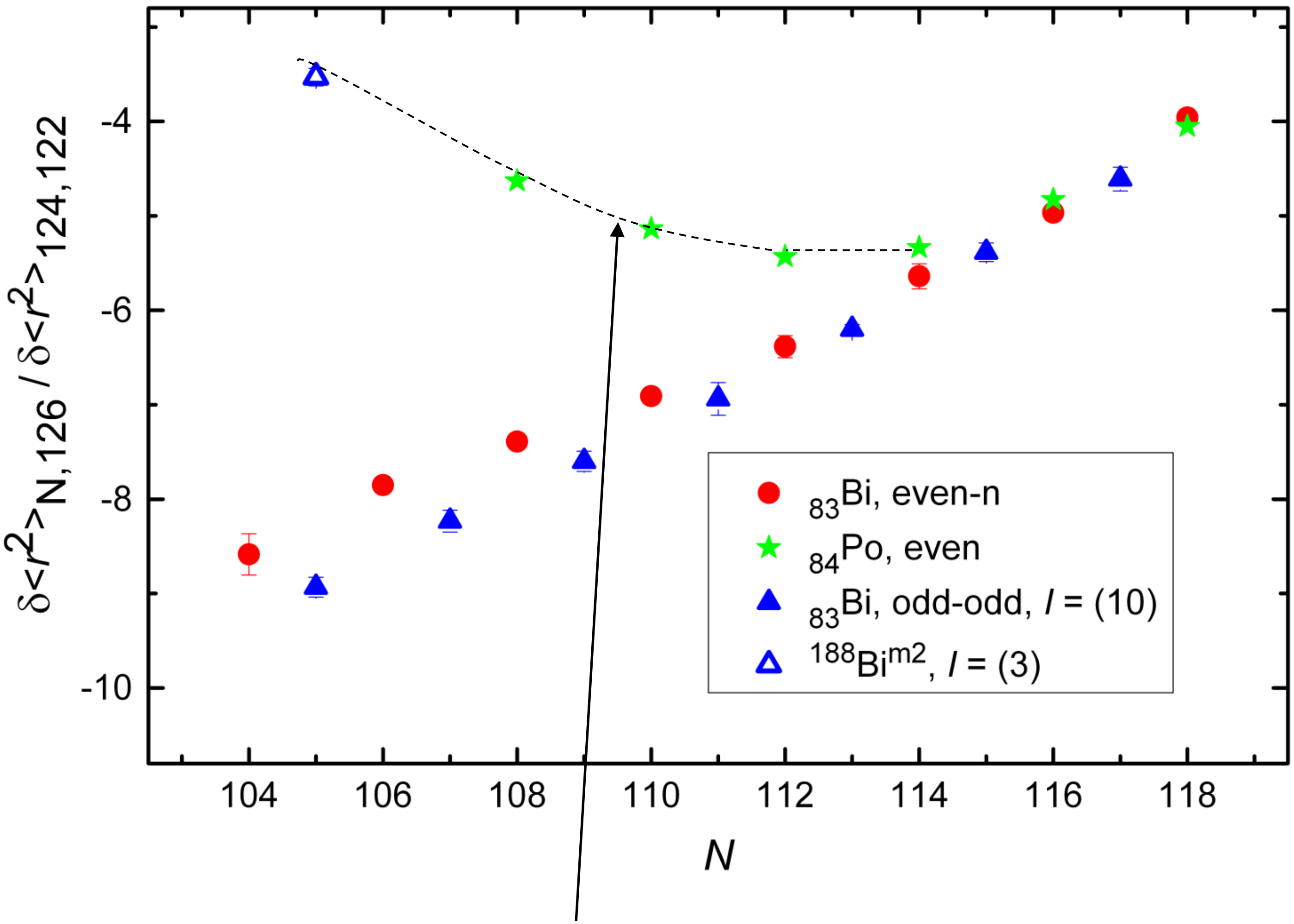


remarkable coincidence of the relative-radii trends for *Z* = 80, 81, 82 at the extensive neutron range

Even-*N* nuclei: shape evolution in the Bi and Tl isotopic chains markedly differs from each other, although these chains are "mirror" in respect to the filled proton shell (Z = 82)

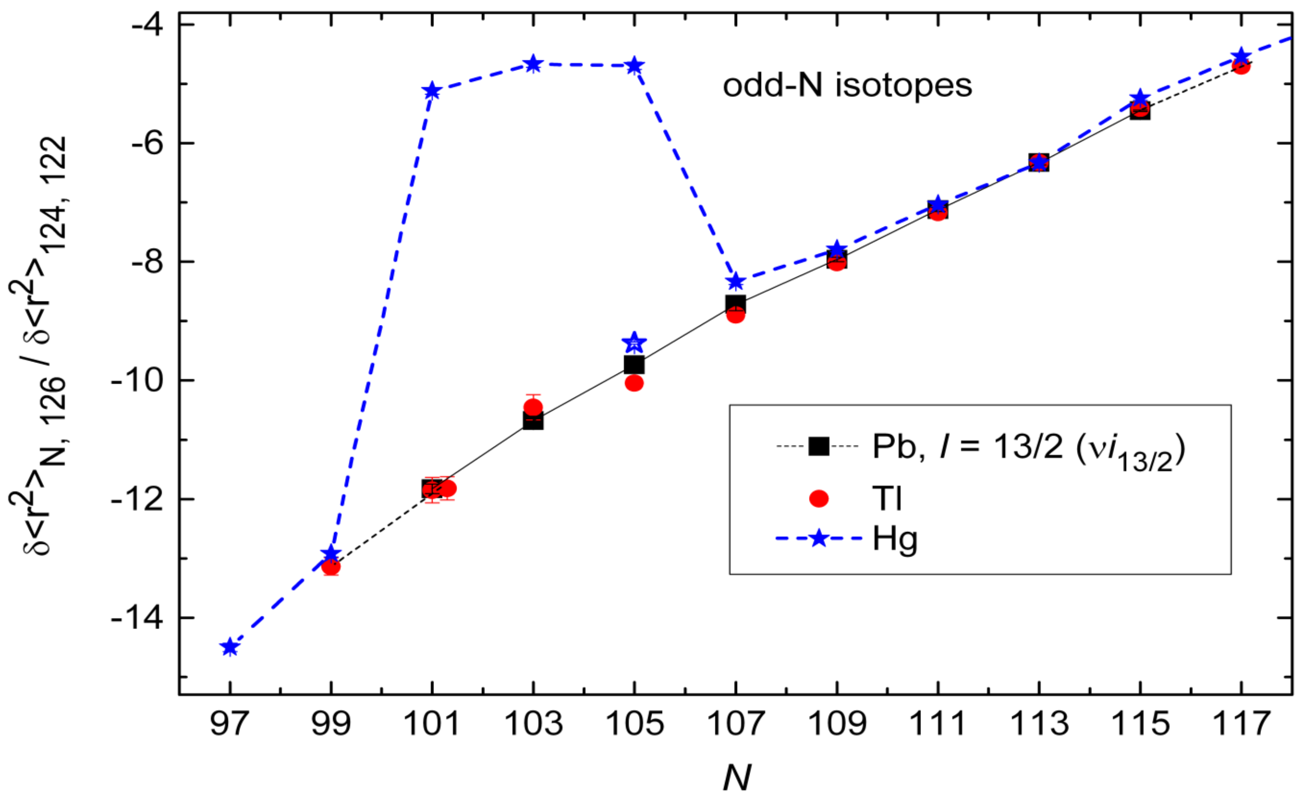
Radii trend for $_{83}$Bi is intermediate between "spherical" $_{82}$Pb trend and $_{84}$Po trend with the onset of deformation

Bi: relative radii



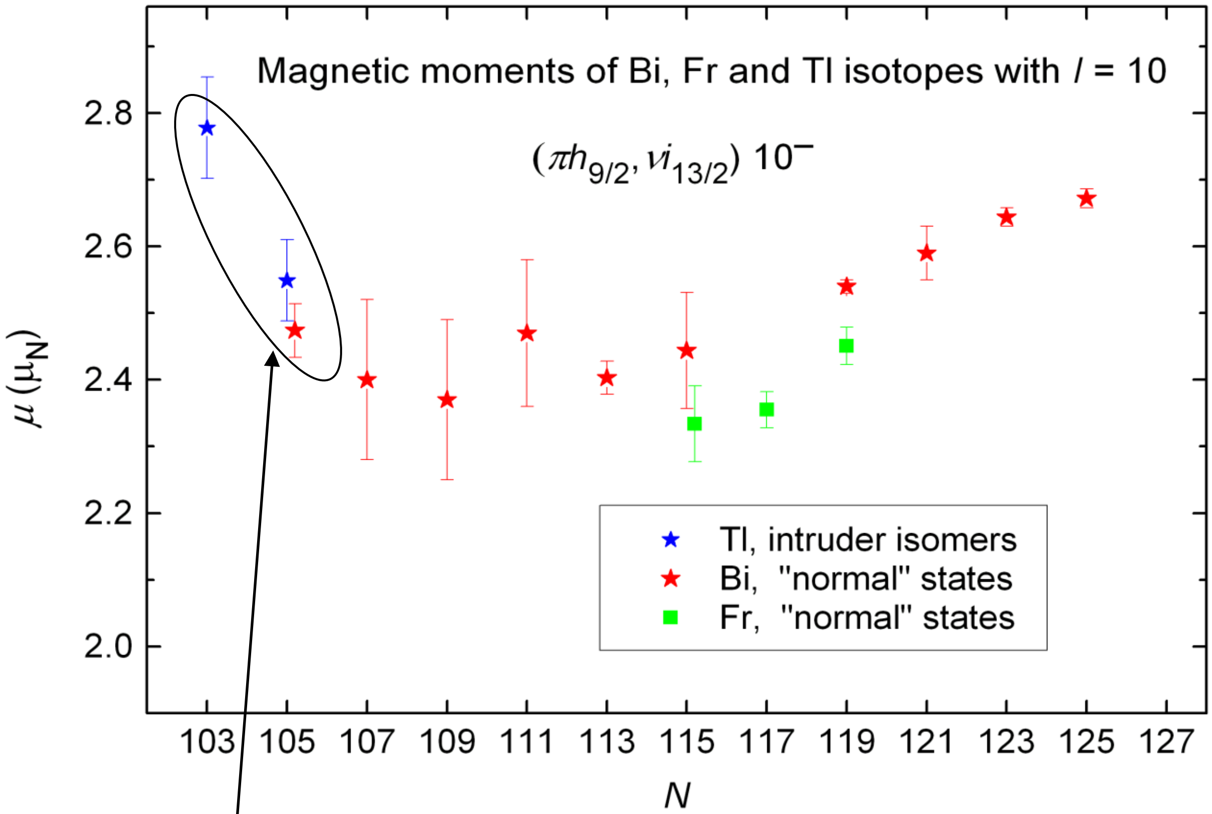
Radius of the strongly deformed ^{188}Bi is found on the continuation of the Po-trend

Comparison of $_{81}$Tl and $_{80}$Hg with $_{82}$Pb



Large prolate deformation for $^{181,\ 183,\ 185}$Hg. Return to “sphericity”: to the same Pb-Tl trend

Bi & Tl: magnetic moments



The increase of μ(10⁻) is connected with the increase of deformation

Bi: main results

1. $\delta\langle r^2\rangle$, μ, Q_s for 25 Bi isotopes/isomers
2. Marked deviation of Bi $\delta\langle r^2\rangle$ trend from (spherical) Pb & Tl trend at $N < 109$, onset of small oblate deformation (?)
3. Large isomer shift (shape coexistence) for intruder isomers
4. Large shape staggering at $A = 188$ ($N = 105$)
5. Systematic behaviour of $I^\pi = 9/2^-$ ($\pi h_{9/2}$) and $I^\pi = 10^-$ ($\pi h_{9/2}$, $\nu i_{13/2}$) magnetic moments, deviation for $A = 215, 217$
6. First isomer selective βDF study (^{188}Bi). Spin dependence of βDF