IRIS & ISOLDE: laser ion source

Эксперименты с лазерным ионным источником:
Изотопы висмута.
(ИРИС, ПИЯФ — ISOLDE, CERN)

А. Е. Барзах, Ю. М. Волков, В. С. Иванов,
П. Л. Молканов, Ф. В. Мороз, С. Ю. Орлов,
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Windmill-ISOLTRAP-RILIS collaboration

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

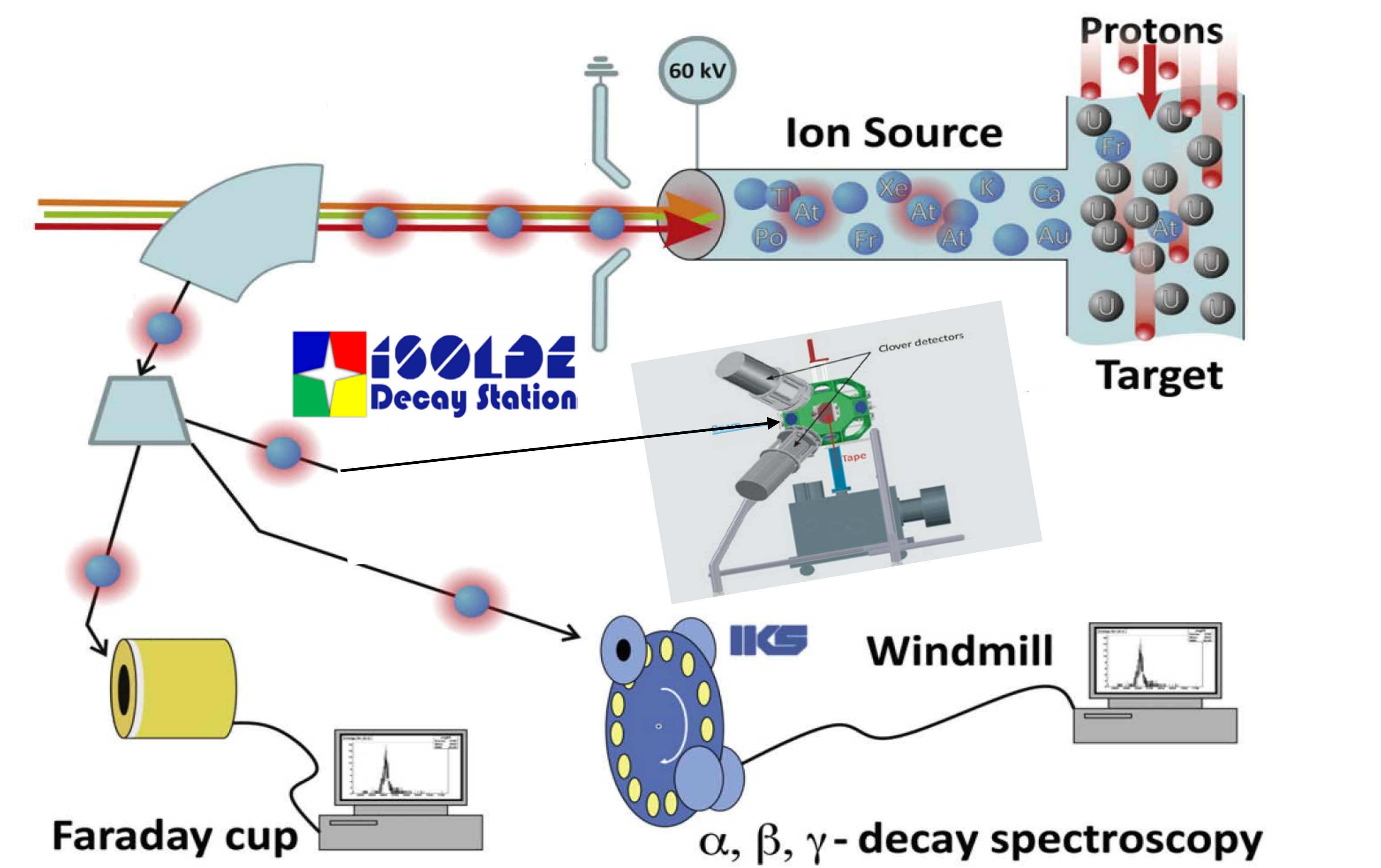
Windmill-ISOLTRAP-RILIS collaboration

PNPI, Gatchina, Russian Federation
RILIS and ISOLDE, Geneva, Switzerland
Institut für Physik, Johannes Gutenberg-Universität Mainz, Mainz, Germany
University of Manchester, UK
MR-TOF@ISOLTRAP team
University of the West of Scotland, United Kingdom
Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Leuven, Belgium
Comenius University, Bratislava, Slovakia
University of York, United Kingdom
… … …

IS 608:

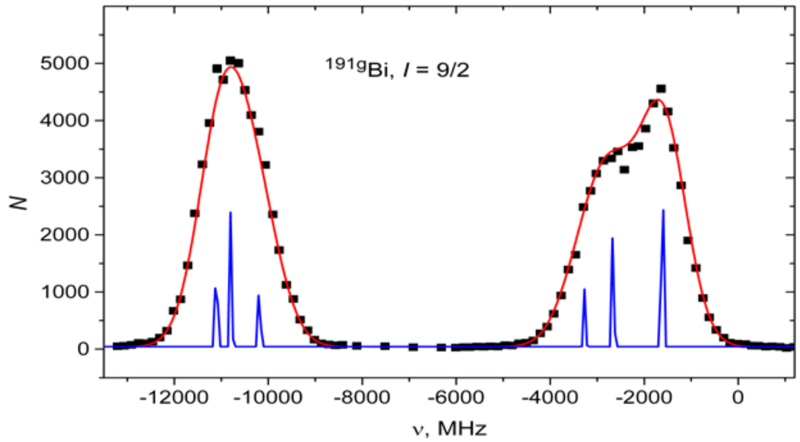
Shape-coexistence and shape-evolution studies for Bi isotopes by in-source laser spectroscopy and beta-delayed fission in ^{188}Bi

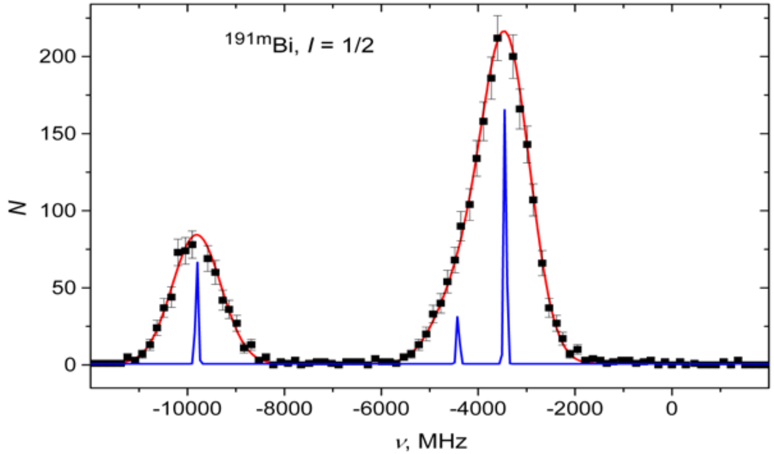
ISOLDE: in-source spectroscopy

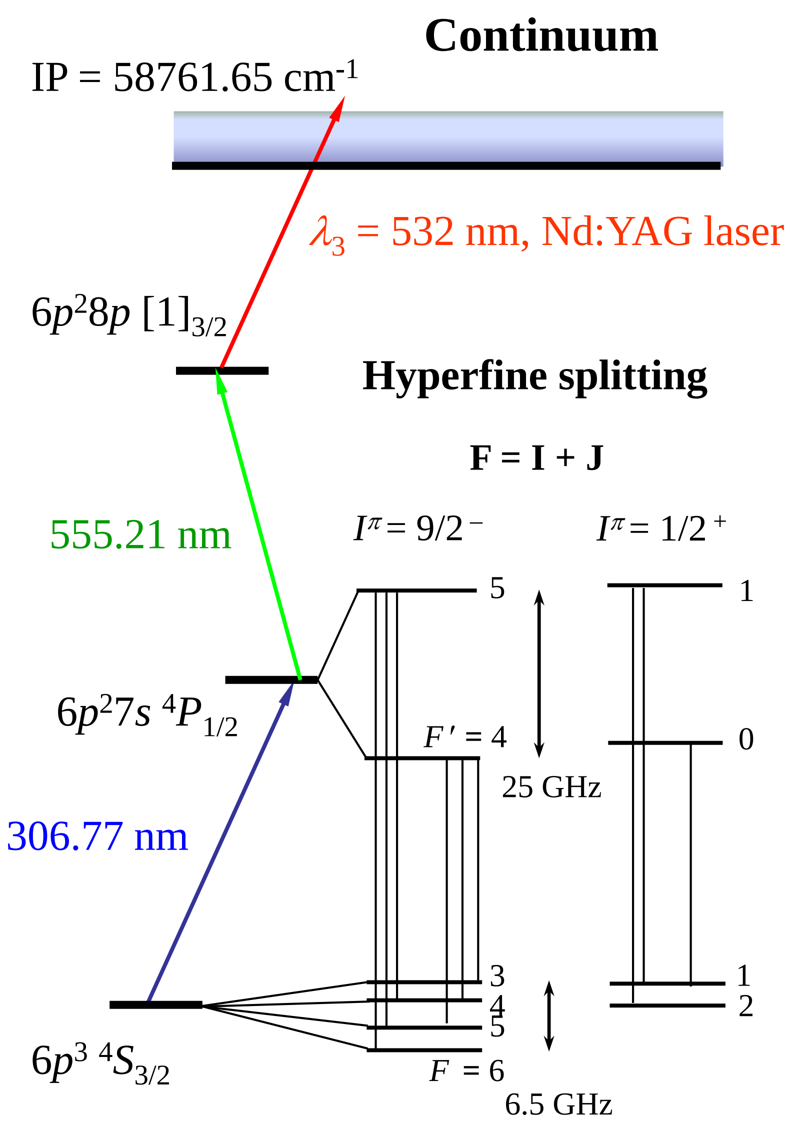


B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)
WM: A.N. Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)
MR-ToF MS: R. N. Wolf et al, NIM, A686, 82 (2012)

Bi: hfs spectra



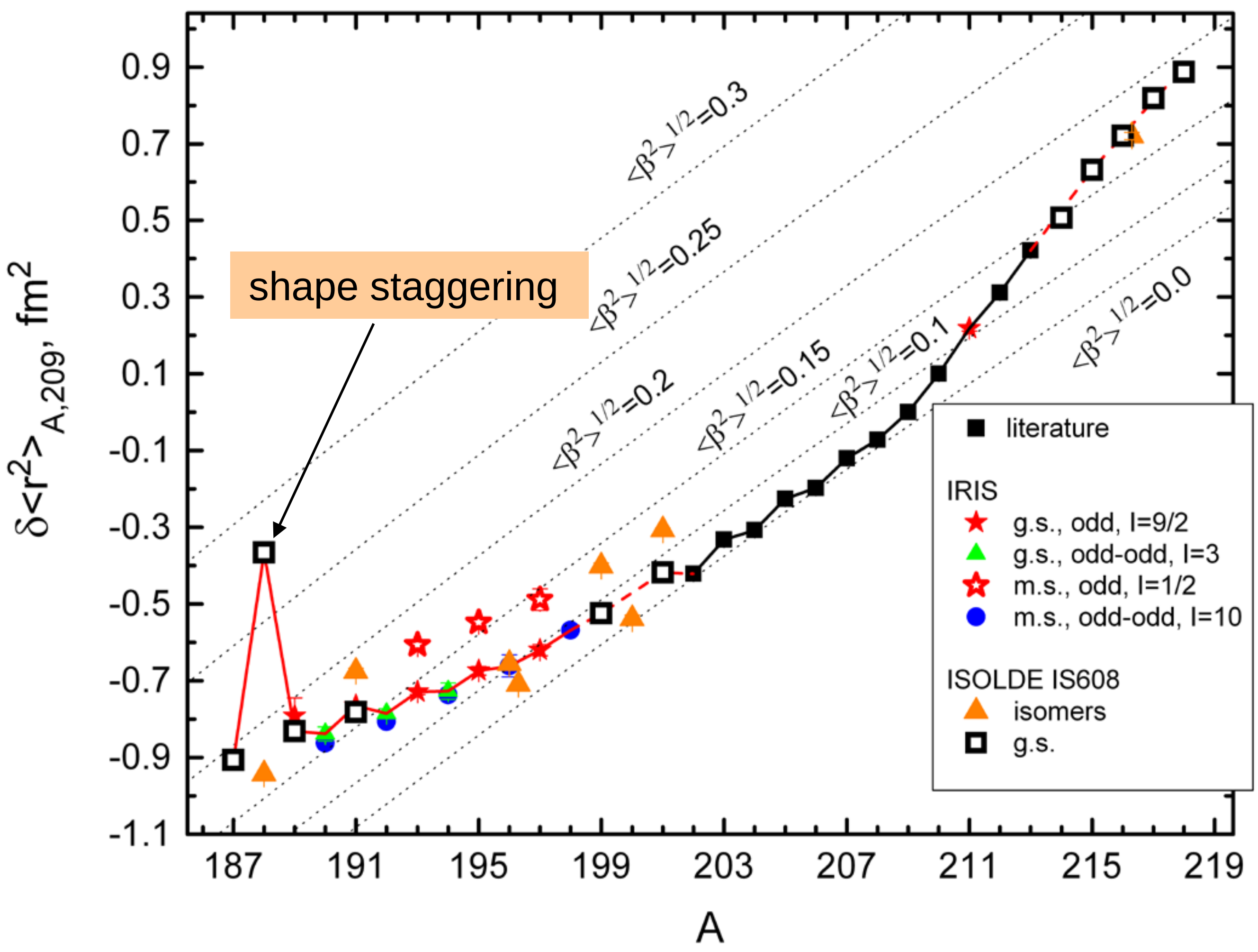




$\delta\nu \sim \delta\langle r^2\rangle$

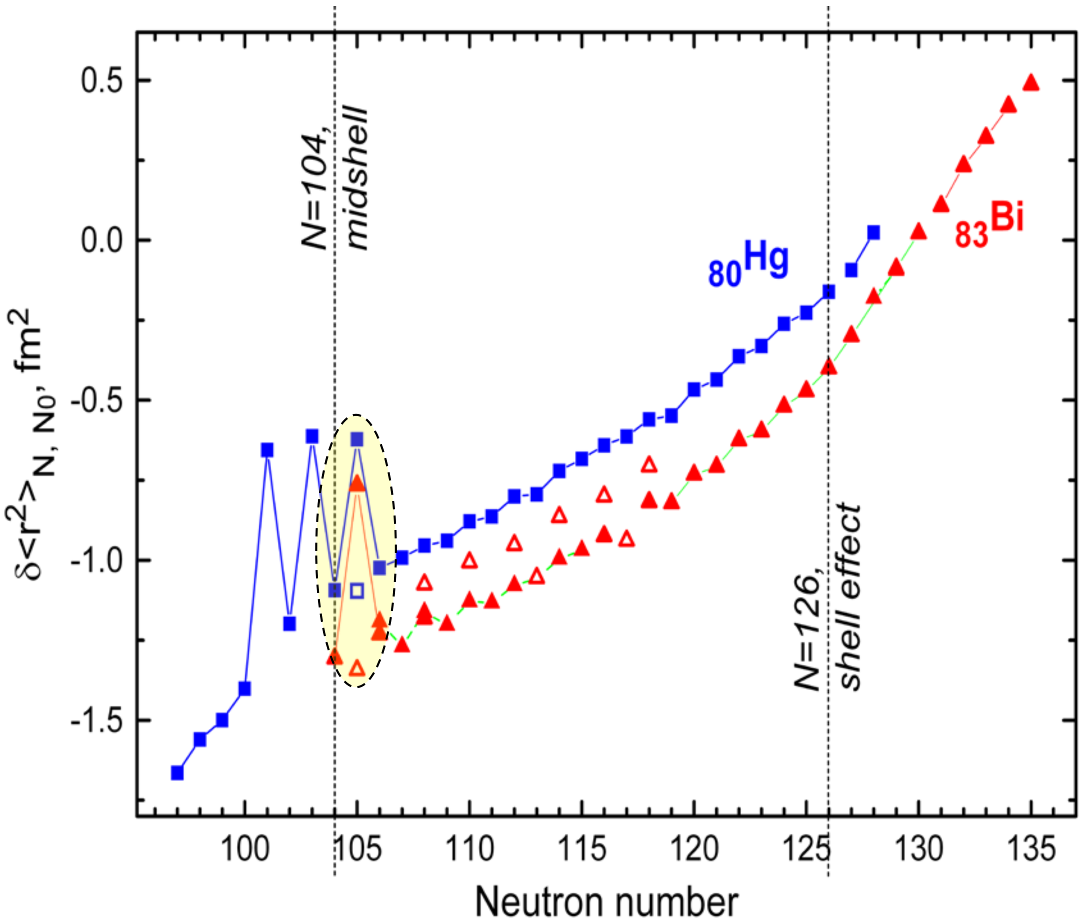
$a \sim \mu,\ b \sim Q$

ISOLDE&IRIS, $_{83}$Bi isotopes: radii



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

Hg and Bi radii



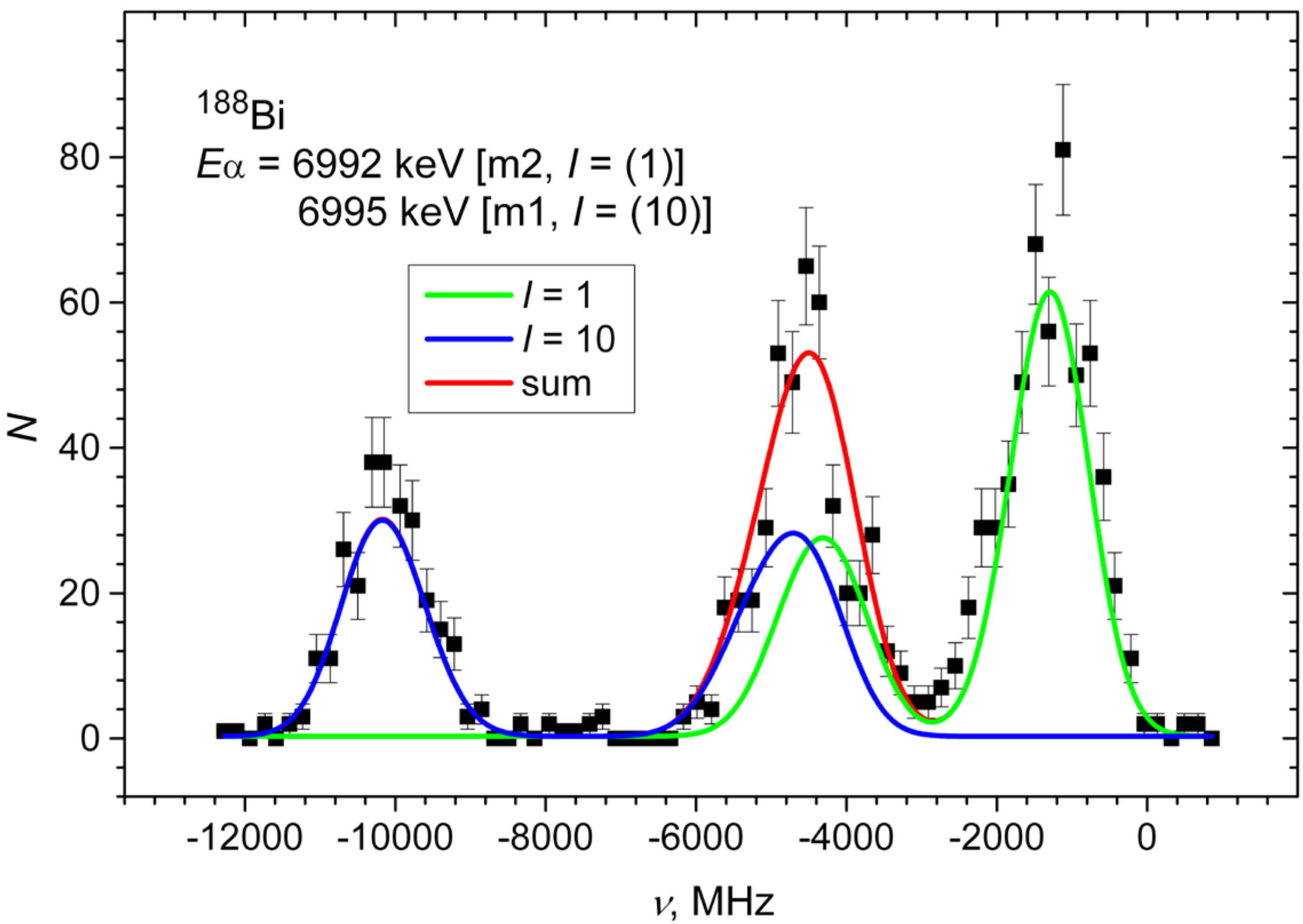
“The huge shape staggering in light Hg isotopes is one of the most remarkable discoveries in nuclear structure physics in the last 50 years”.

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

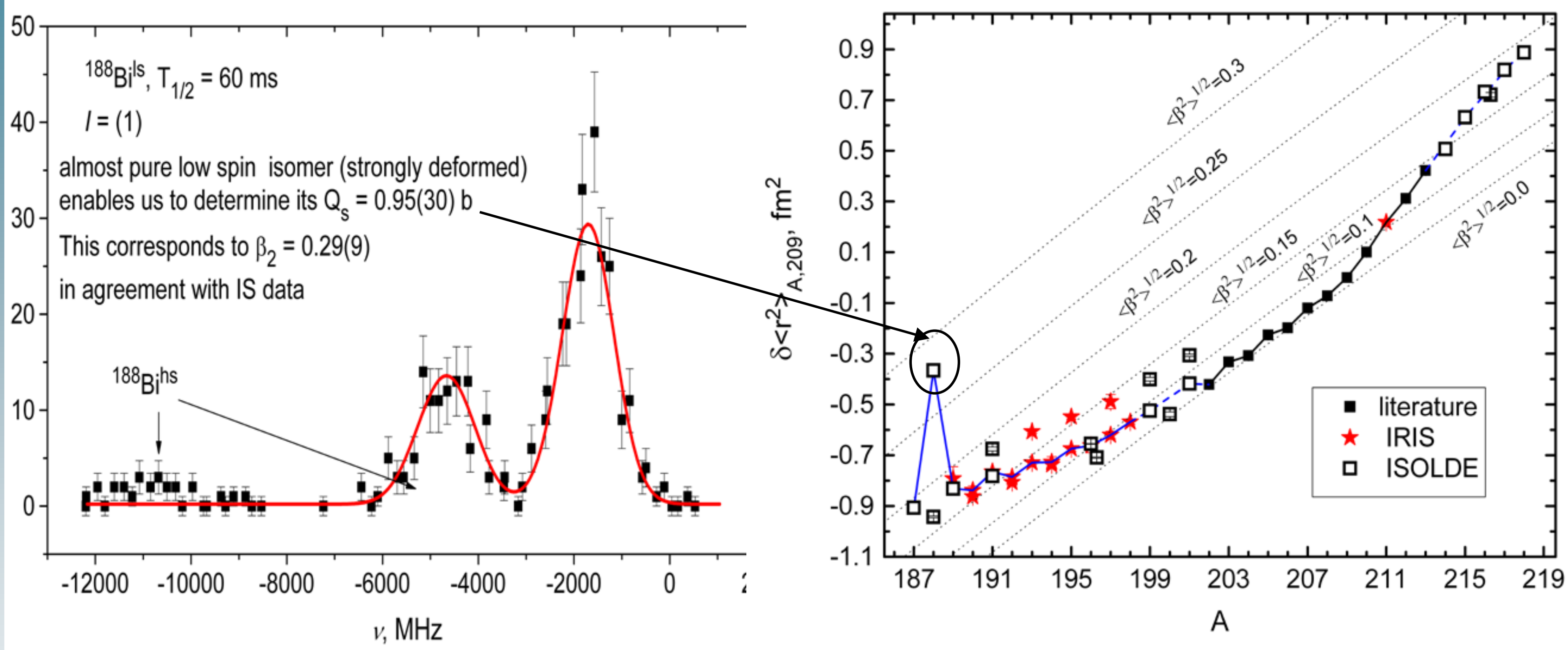
$$Q_s = \frac{I \cdot (2I-1)}{(I+1)\cdot(2I+3)} \cdot \frac{3}{\sqrt{5\pi}} \cdot Z \cdot R_0^2 \cdot \beta_Q \cdot \left(1 + \frac{1}{7}\cdot\sqrt{\frac{20}{\pi}} \cdot \beta_Q + \dots\right)$$

^{188}Bi: 2016 run

Two isomers: low spin (strongly deformed) and high spin (near spherical)



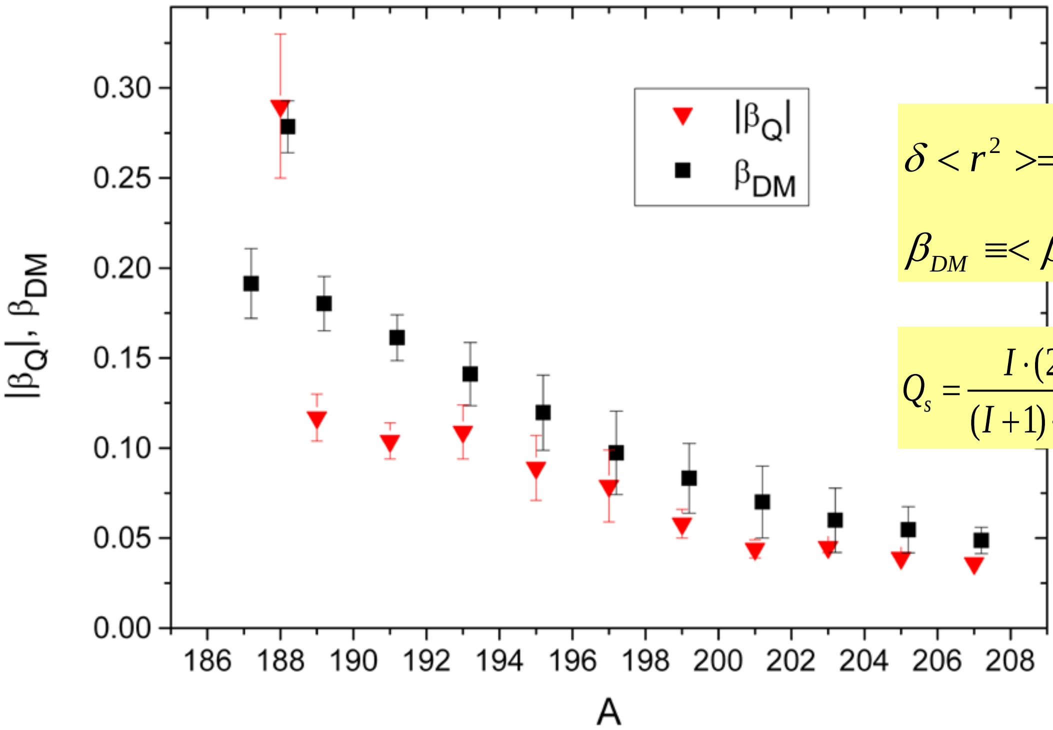
^{188}Bi: 2017 run



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



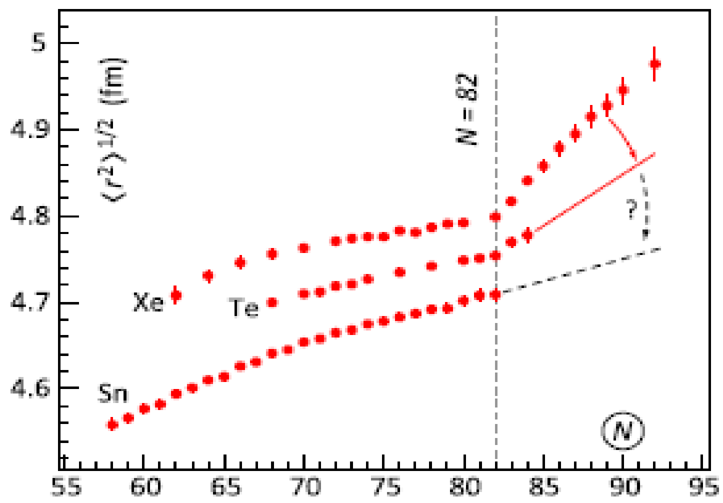
$$\delta < r^2 > = \delta < r^2 >_{DM} + \frac{5}{4\pi} < r^2 >_{DM} \; \delta < \beta_{DM}^2 >$$

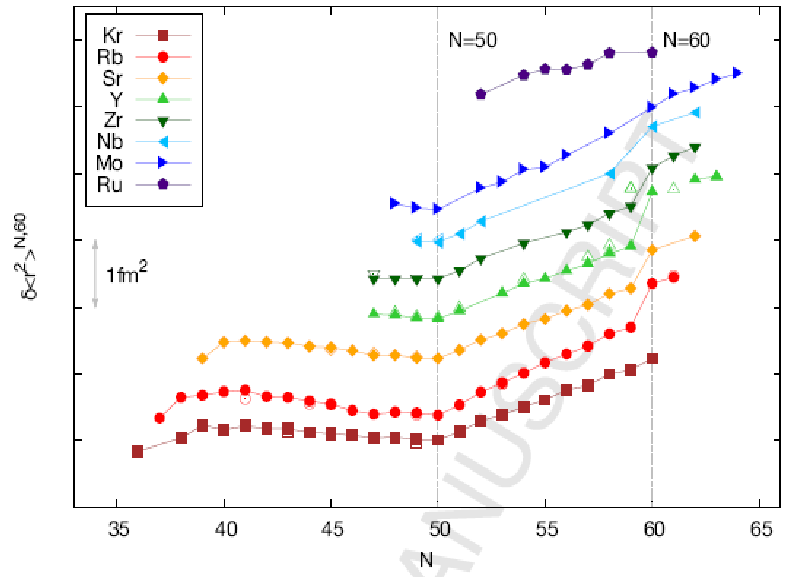
$$\beta_{DM} \equiv < \beta_{DM}^2 >^{1/2}$$

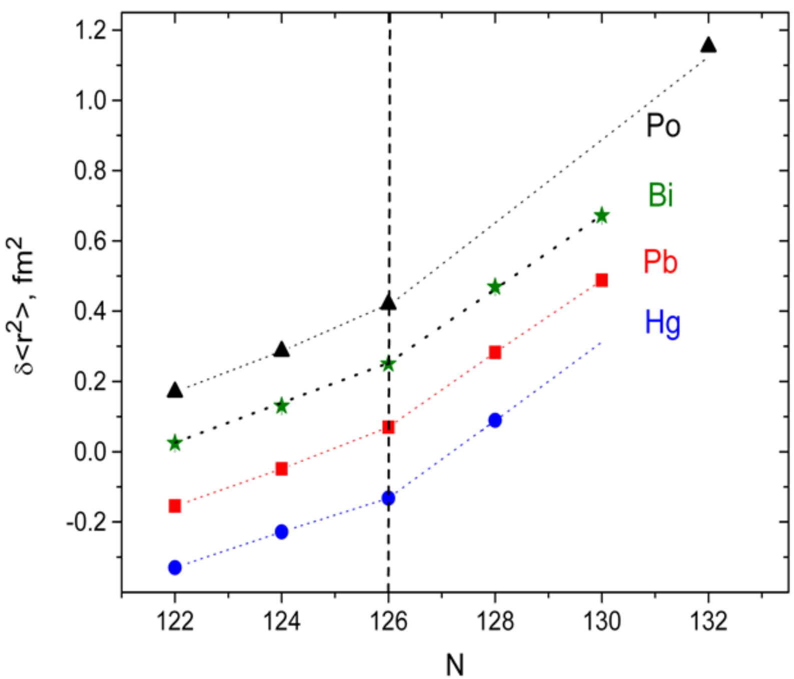
$$Q_s = \frac{I \cdot (2I-1)}{(I+1)\cdot(2I+3)} \cdot \frac{3}{\sqrt{5\pi}} \cdot Z \cdot R_0^2 \cdot \beta_Q \cdot (1 + \frac{1}{7} \cdot \sqrt{\frac{20}{\pi}} \cdot \beta_Q + \ldots)$$

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

Shell-effect in radii at $N = 50, 82, 126$

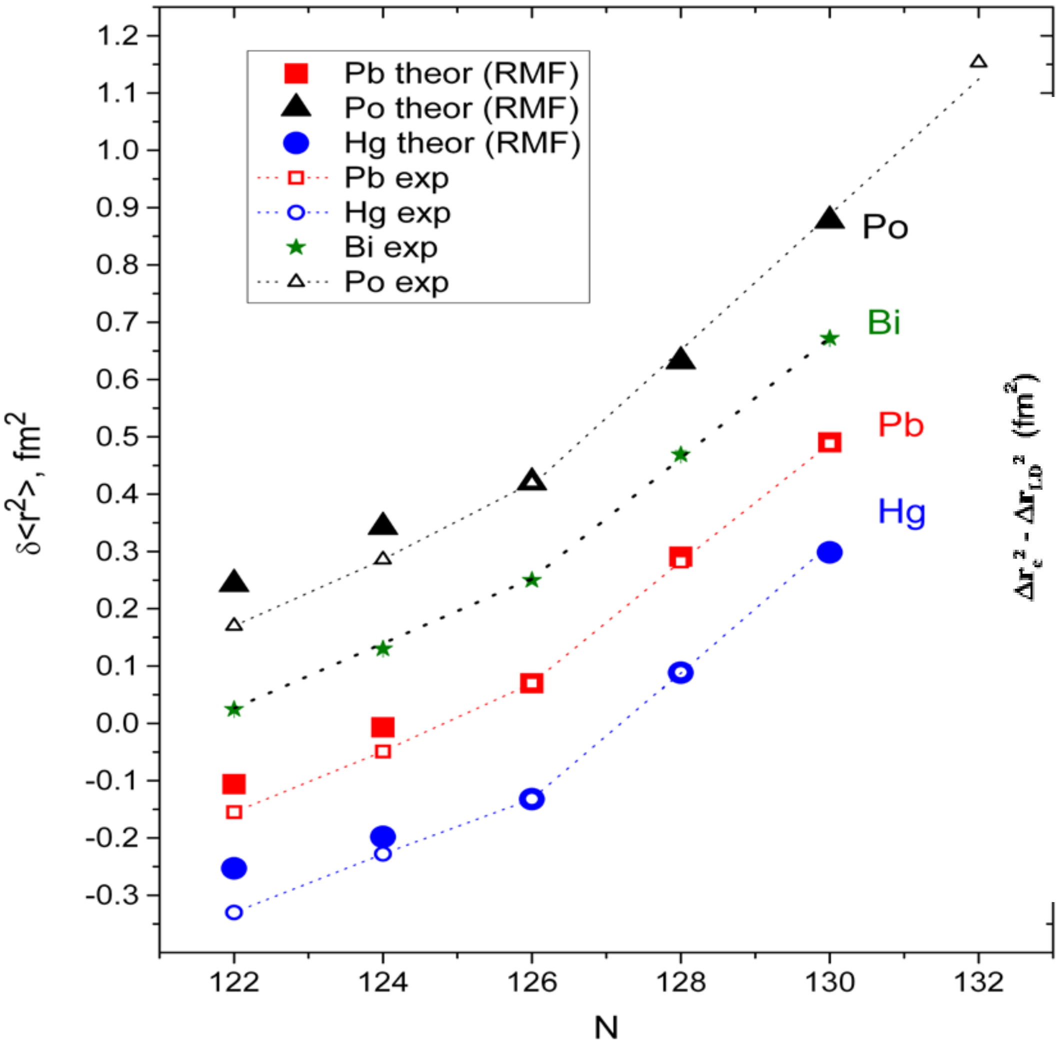


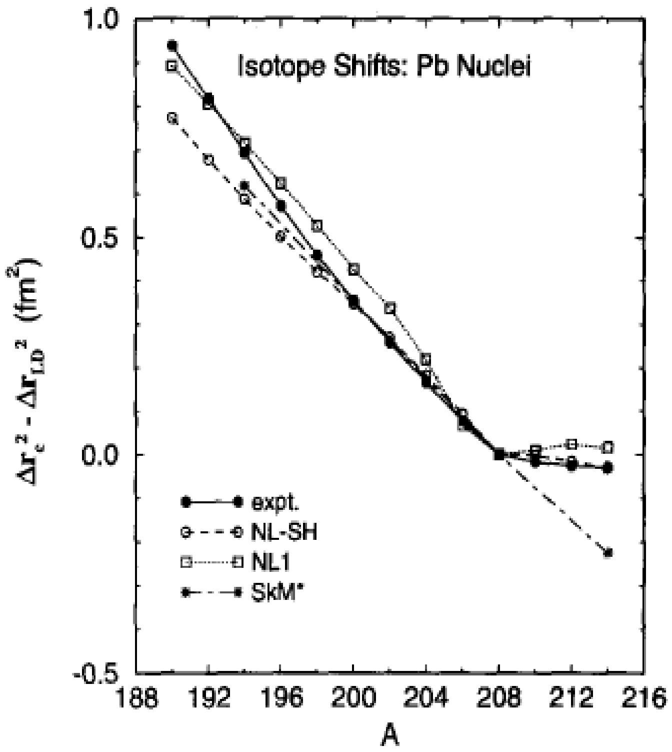




The shell effect in the changes of the nuclear mean-square charge radius $\delta\langle r^2\rangle$ — the kink in its isotopic trend at the magic neutron numbers — was found to be an universal feature of the $\delta<r^2>$ behavior

Shell effect in radii: comparison with RMF theory

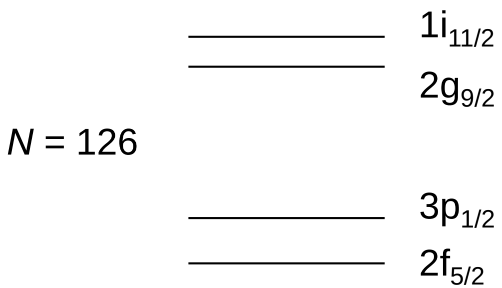




S. E. Agbemava, A. V. Afanasjev, D. Ray, and P. Ring, Phys. Rev. C **89**, 054320 (2014)

Shell effect in radii: theory

The reproduction of the isotope shift in lead is by and large determined by
the occupation of the $1i_{11/2}$ neutron orbital.
P. M. Goddard, P. D. Stevenson, and A. Rios, Phys. Rev. Lett. **110**, 032503 (2013)



As the s.p. function of $n1i_{11/2}$ has a larger radius than those of the neighboring orbits, the attraction between protons and neutrons makes $\langle r^2 \rangle$ larger as $n1i_{11/2}$ is occupied to greater degree.

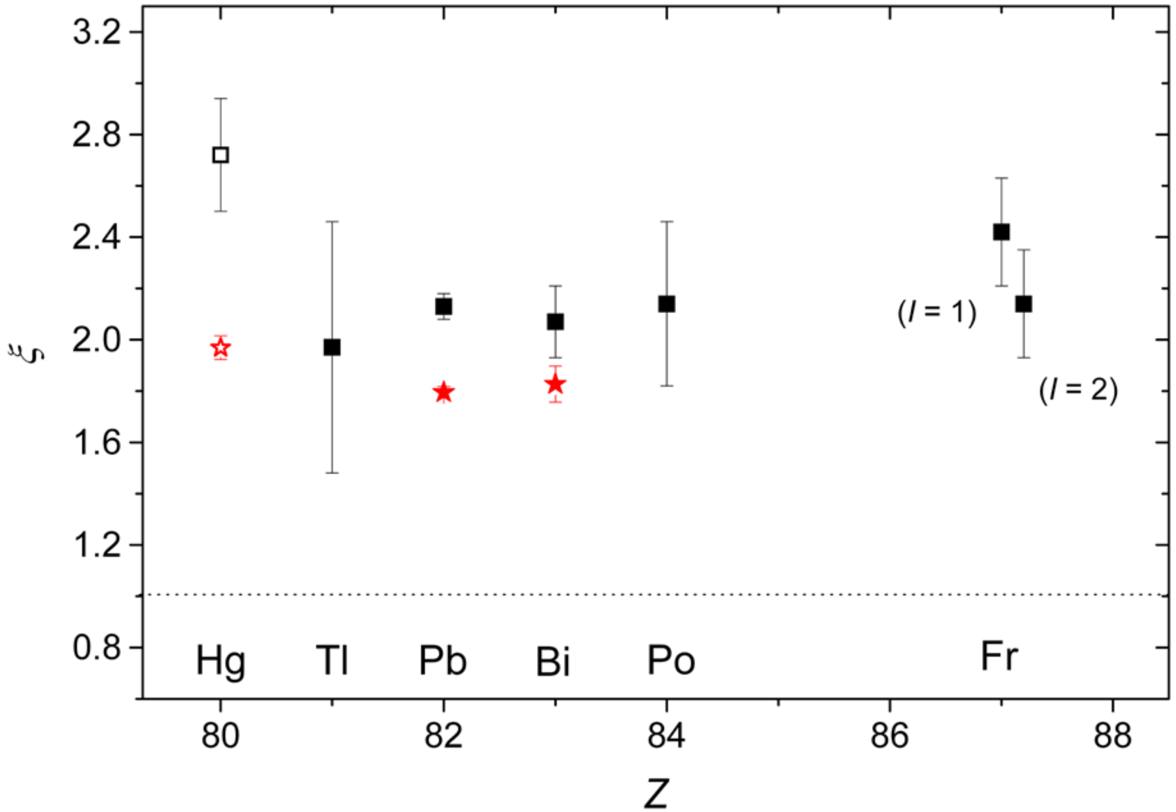
$i_{11/2}$ state is populated due to pairing

HFB with density-depended LS interaction based on 3N forces from effective field theory
H. Nakada and T. Inakura, Phys. Rev. C **91**, 021302(R) (2015)

Relativistic Hartree-Fock theory with non-linear terms and density-dependent meson-nucleon coupling
B. Kumar, S. K. Singh, B. K. Agrawal, S. K. Patra, Nucl. Phys. A **966**, 197 (2017)

Energy density functional method based on the theory of finite Fermi systems
S. A. Fayans, S. V. Tolokonnikov, E. L. Trykov, D. Zawischa, Nucl. Phys. A **676**, 49 (2000)
P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 95, 064328 (2017)

Shell effect in radii: even-*N* and odd-*N* nuclei

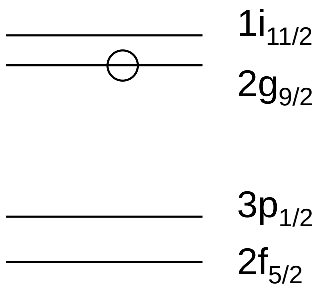


$$\xi_{even} \equiv \frac{\delta\langle r^2\rangle_{128,126}}{\delta\langle r^2\rangle_{126,124}}$$

$$\xi_{odd} \equiv \frac{\delta\langle r^2\rangle_{127,126}}{\delta\langle r^2\rangle_{125,124}}$$

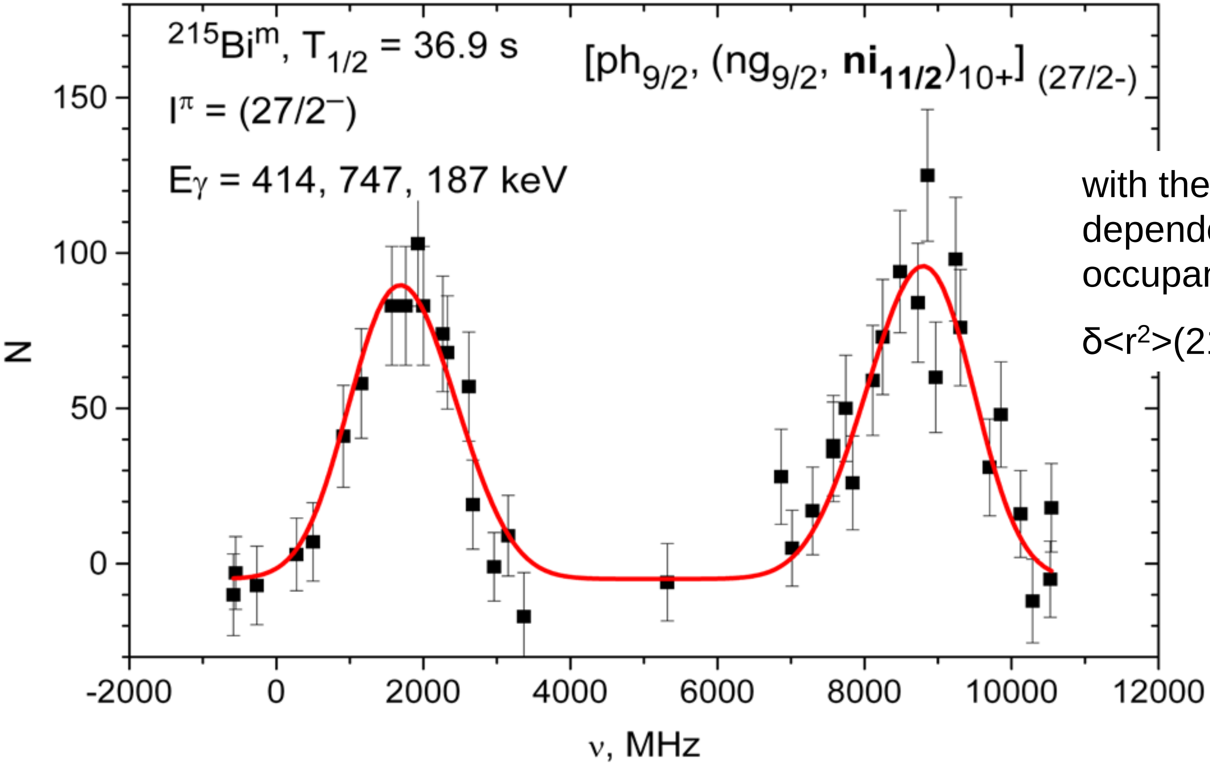
$$\xi_{odd} \approx \xi_{even} \approx 2$$

N = 126



For *N* = 127 the occupancy of the $n1i_{11/2}$ state is equal to zero (pairing is absent). Correspondingly, all models with the kink explanation by the increase of this occupancy predict $\xi_{odd} \sim 1$ in contradiction with experiment

Bi: shell effect — occupancy of the $ni_{11/2}$ shell?



with the assumption of the linear dependency of ξ on the $nh_{11/2}$ occupancy:

$\delta\langle r^2\rangle$(215m-215g) ~ 0.10÷0.05 fm^2

ground state: $ph_{9/2}$

additivity relation:

$$\mu_{add} = \frac{I}{2}\left(\frac{\mu_p}{i_p} + \frac{\mu_n}{i_n}\right) + \frac{I}{2}\left(\frac{\mu_p}{i_p} - \frac{\mu_n}{i_n}\right) \cdot \frac{i_p \cdot (i_p + 1) - i_n \cdot (i_n + 1)}{I \cdot (I + 1)}$$

μ_{exp} = 3.13(5) n.m.

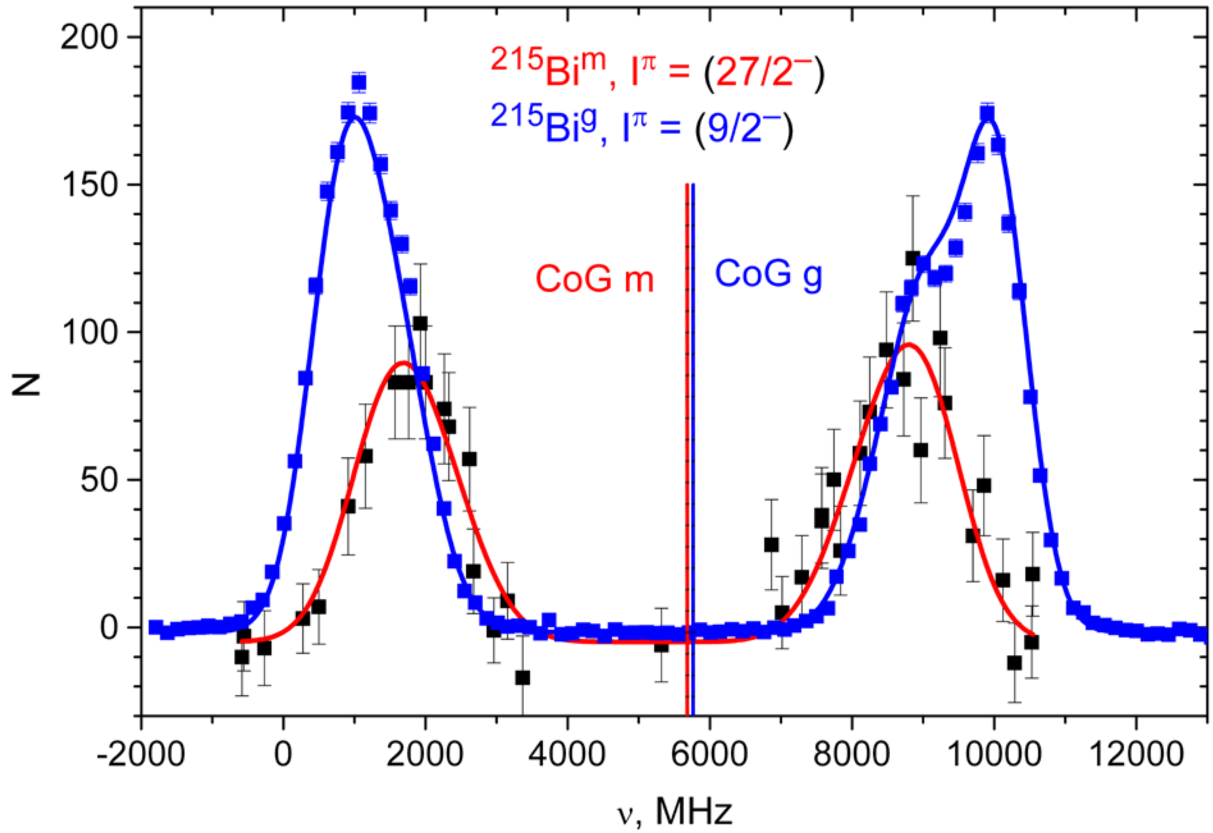
for configuration $[ph_{9/2}, (ng_{9/2}, ni_{11/2})]_{27/2}$:

μ_{add} = 3.0 n.m.

⇓

confirmation of the configuration assignment

Bi: shell effect — occupancy of the $ni_{11/2}$ shell?

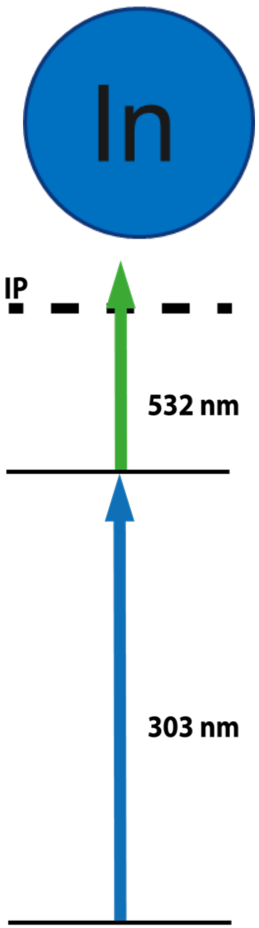


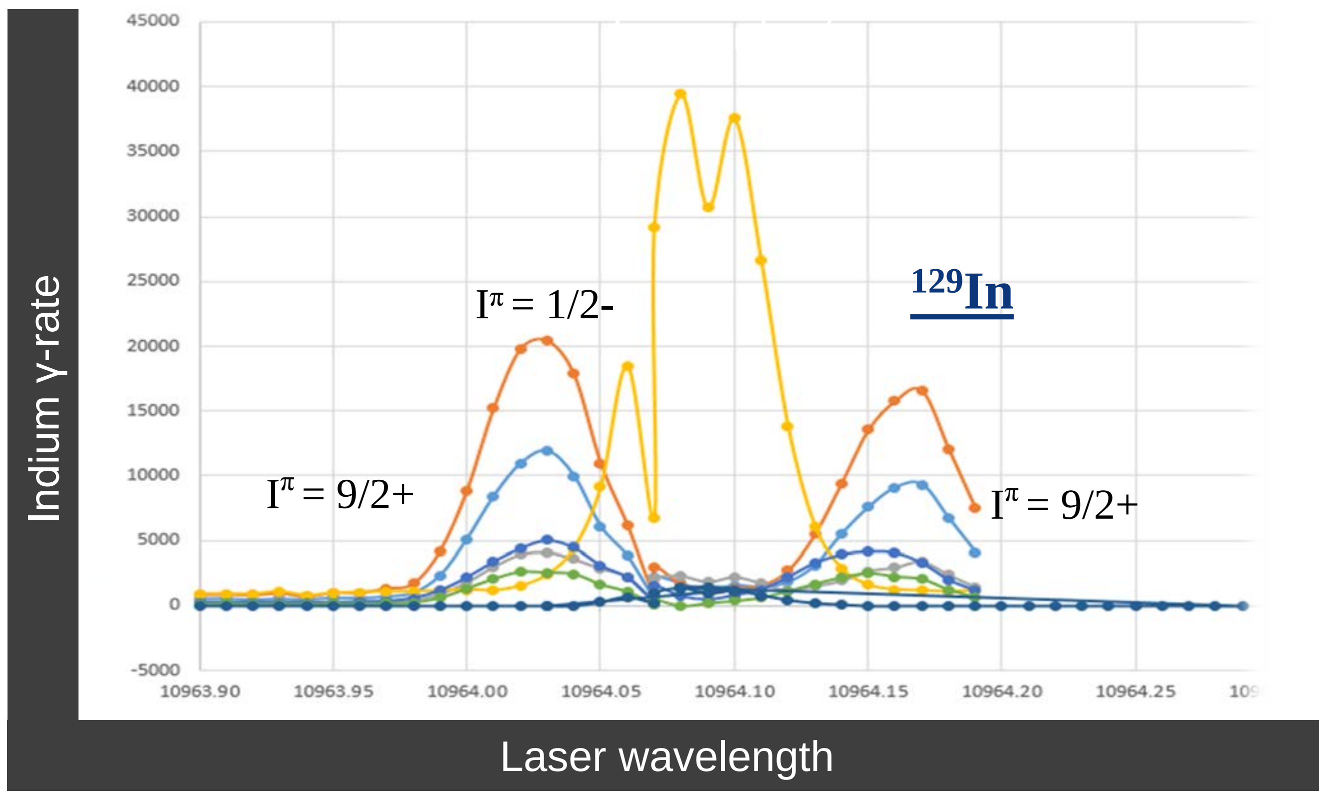
configutations:
[$ph_{9/2}$] *vs*
[$ph_{9/2}$, ($ng_{9/2}$, $ni_{11/2}$)]

prediction:
isomer shift ~ 0.10÷0.05 fm^2

exp. isomer shift: 0.005(10) fm^2
no influence of $ni_{11/2}$ state occupancy!

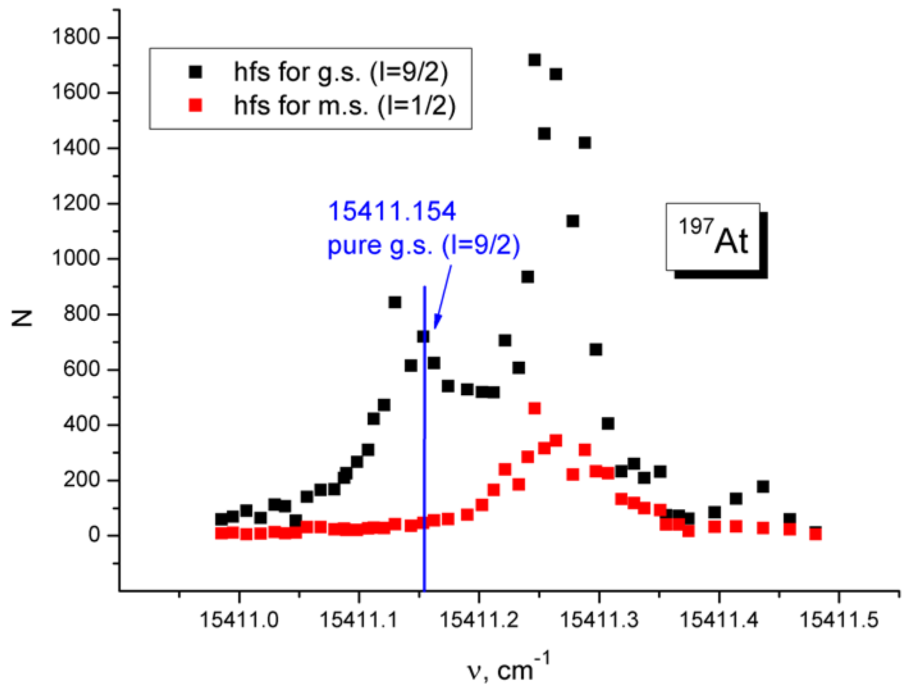
Isomer selective ionization of In

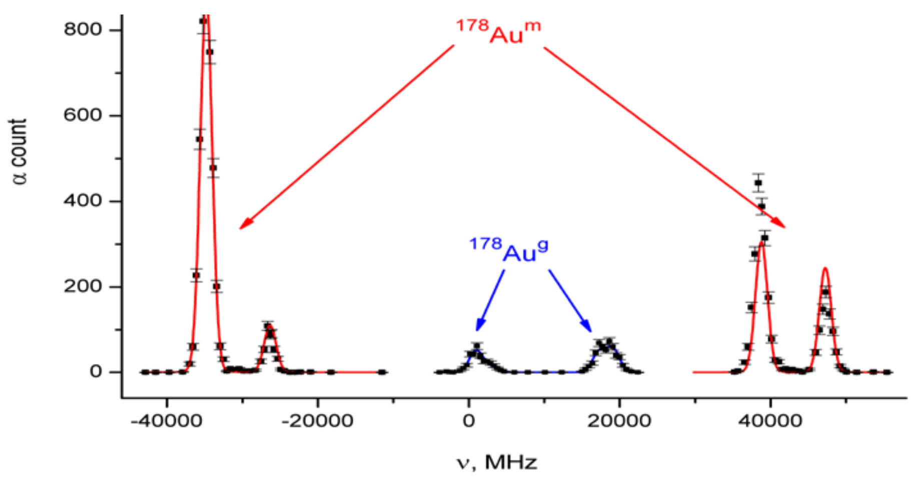




Excited states in ^{133}Sn (double magic + 1 neutron) were studied via the β-decay of the separated isomers of ^{133}In.

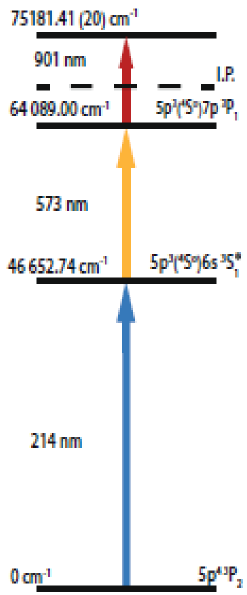
High-precision isomer-selective Penning-trap mass spectrometry in the neutron-deficient lead region

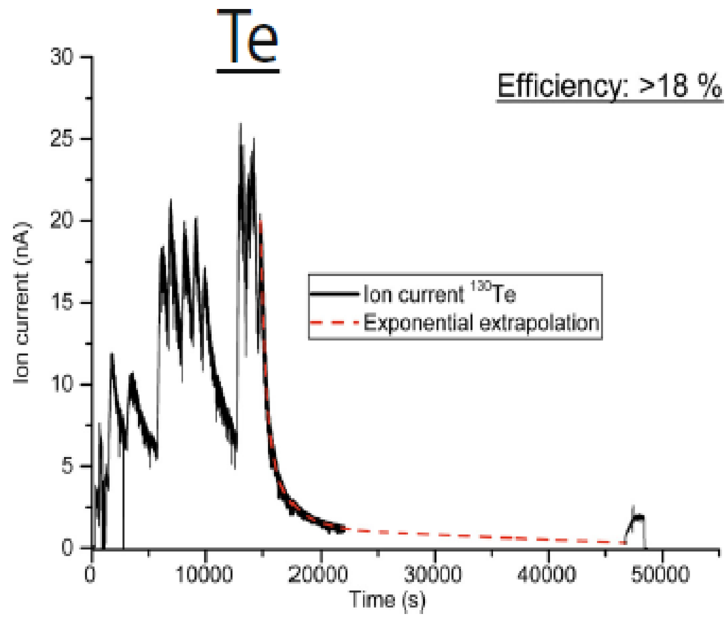


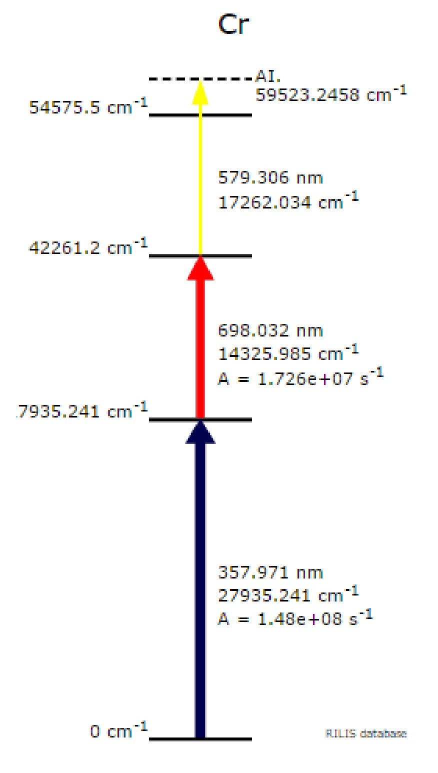


Mass measurements became possible only due to the isomer selectivity of RILIS

Ionization schemes for Te and Cr







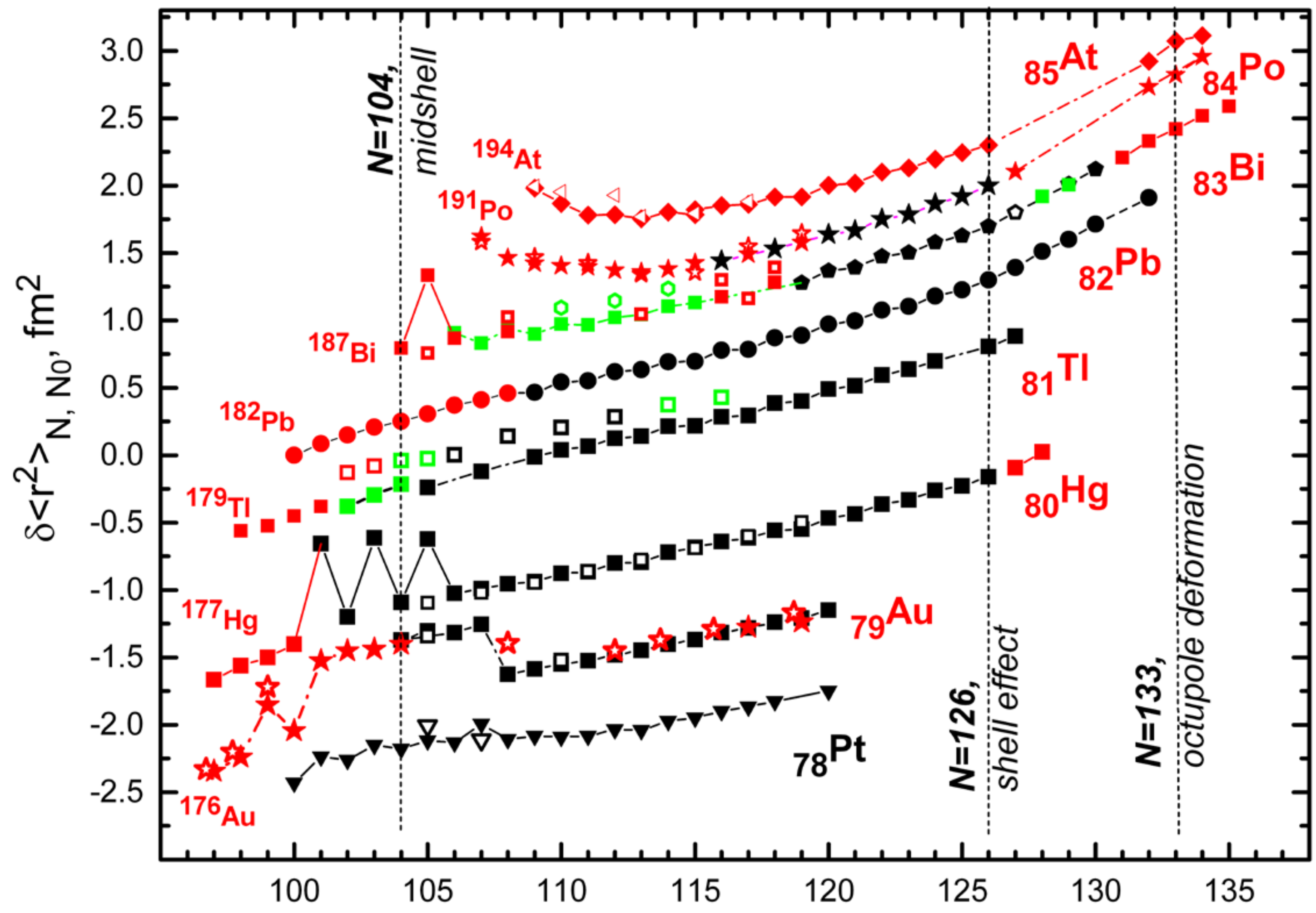
Te

T. Ahn et al., *Coulomb Excitation of ^{116}Te and ^{118}Te: a Study of Collectivity Above the Z=50 Shell Gap*, Technical Report

Cr

S. Kreim et al., *Seeking the Purported Magic Number N = 32 with High-Precision Mass Spectrometry*. Technical report

Shape coexistence study in the Pb region



more than 120 isotopes/isomers were studied

Bi: основные результаты (2017)

1. Измерение квадрупольного момента (статической деформации) $^{188}Bi^{m}$ — подтверждение интерпретации staggering'а радиуса при N = 105 скачками деформации
2. Измерение и анализ оболочечного эффекта в радиусах Bi — опровержение общепринятой интерпретации этого эффекта изменением заселенности $\nu i_{11/2}$ состояния
3. Подтверждение конфигурации с неспаренным нейтроном у $^{215}Bi^{m}$; отсутствие изомерного сдвига свидетельствует об отсутствии влияния состояния $\nu h_{11/2}$ на оболочечный эффект
4. Новые возможности установки RILIS: изомерно селективное исследование In, At, Au; эффективные схемы ионизации для Cr и Te

Bi: main new results

1. Quadrupole moment measurement for $^{188}Bi^{m}$ — confirmation of the shape staggering at $N = 105$
2. Shell effect in Bi radii — undermining the commonly adopted theoretical interpretation by the $\nu i_{11/2}$-state occupancy
3. Confirmation of the configuration assignment for $^{215}Bi^{m}$; zero isomer shift — no influence of the $\nu h_{11/2}$ occupancy
4. New RILIS opportunities: isomer selective production of In, At, Au; efficient ionization scheme for Cr and Te