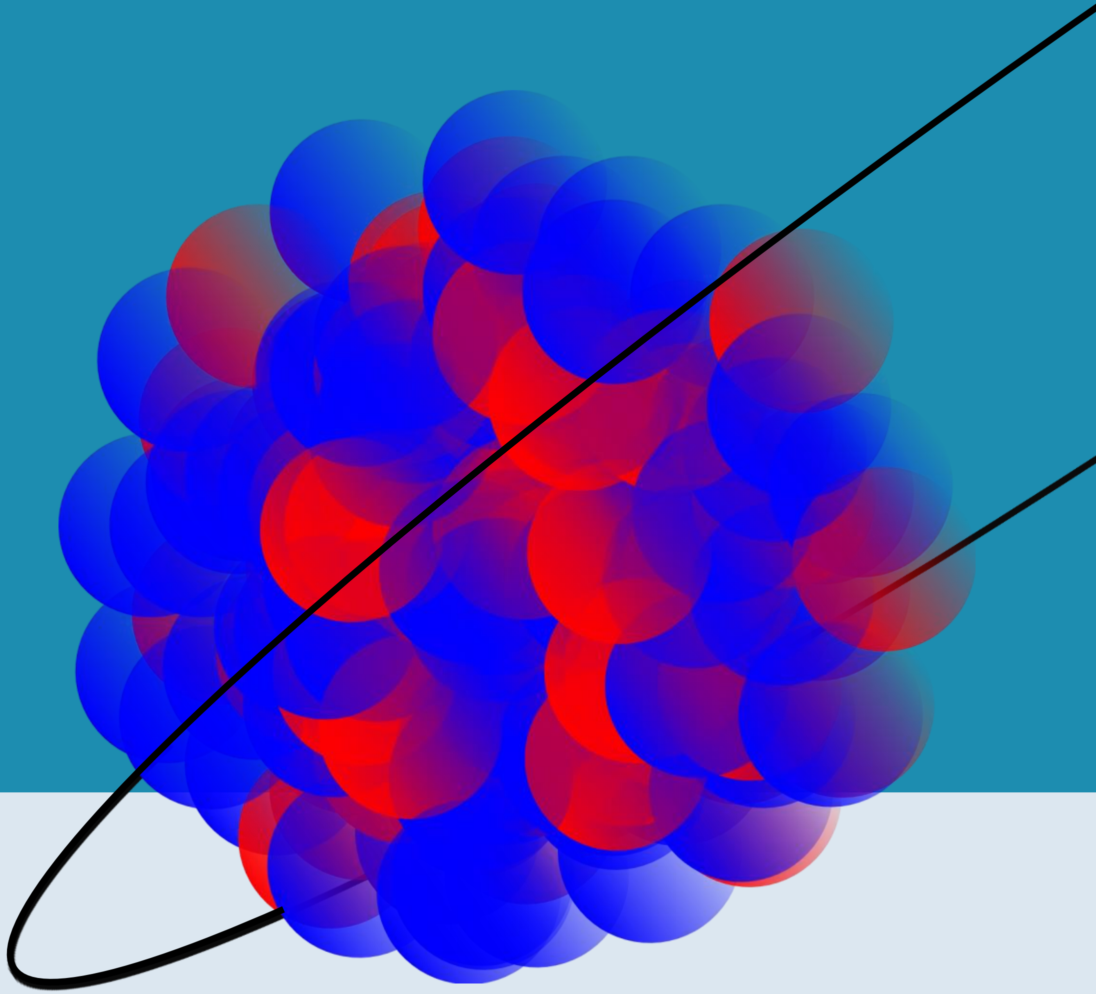
KU LEUVEN
NUCLEAR AND RADIATION PHYSICS

IS456

Study of polonium isotopes ground-state properties by simultaneous atomic & nuclear spectroscopy



Spokesperson: Prof Thomas Elias Cocolios
Local contact: Dr Reinhard Heinke

IS456: 22.5 shifts remaining

- IS456 so far
  - Shape evolution across the isotopic chain
  - Kink and odd-even staggering
  - Complementary decay spectroscopy
- Remaining scientific case
  - Long-lived high-spin isomers just beyond N=126
  - Neutron-rich isotopes near N=136
- Challenges and how to address them
  - From the LIST to the 2-repeller LIST
  - Detection setups

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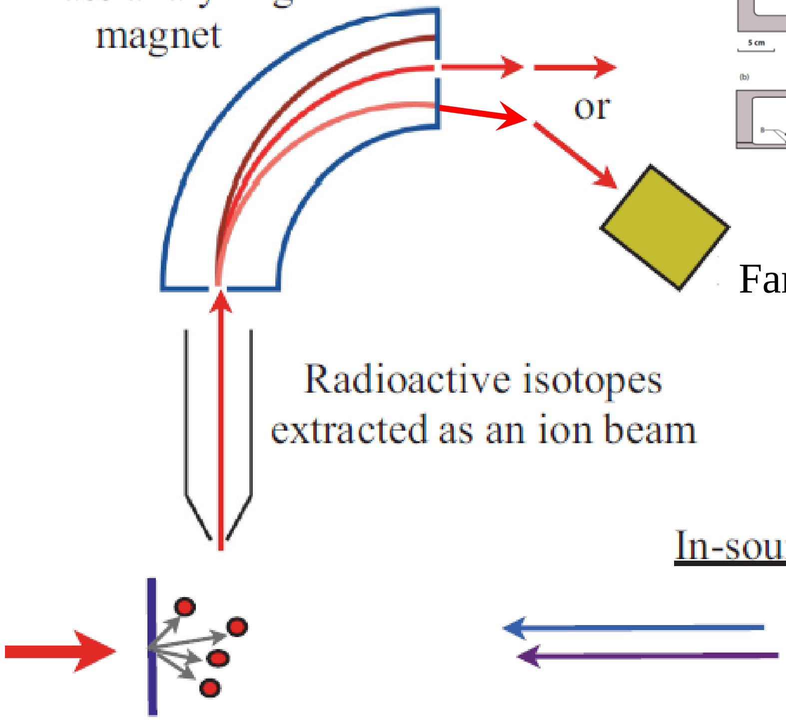
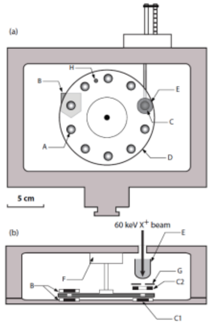
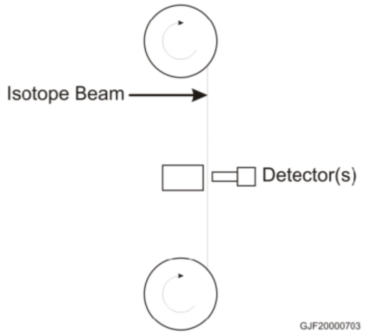
IS456: in-source laser spectroscopy





Decay spectroscopy using either the Windmill (LA1/2 or GLM) or the ISOLDE Tape Station (CA0)



Free decay data during collection!

<u>In-source method</u>

Laser beams step-wise resonantly ionize the reaction products leaving the target (one laser will scan over the resonances)

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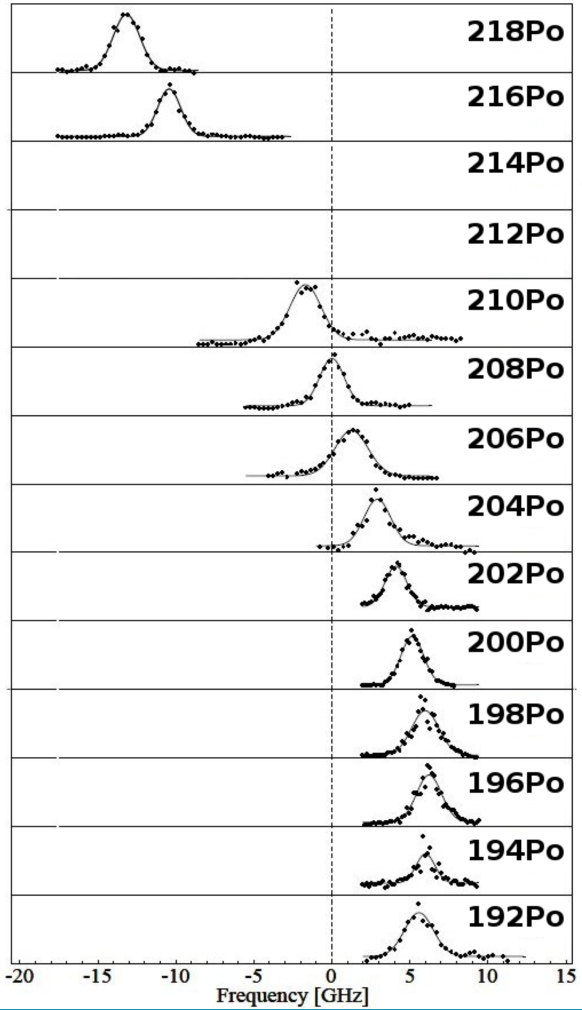
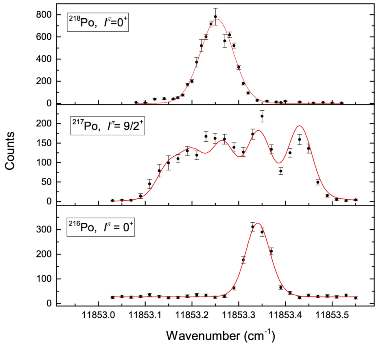
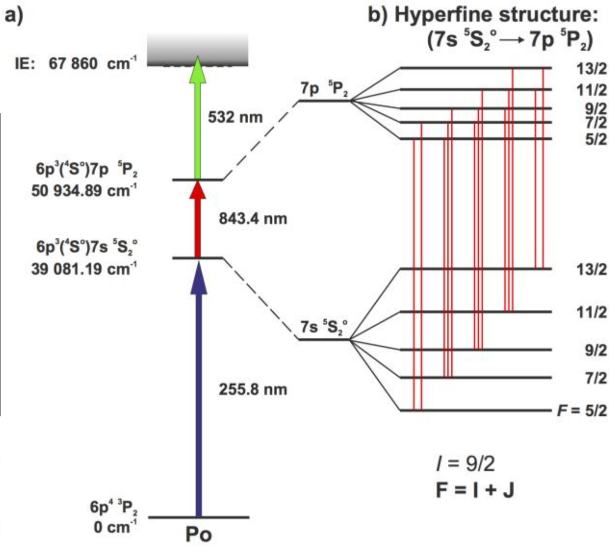
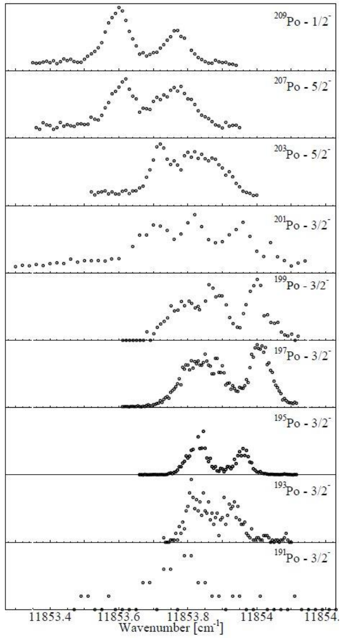
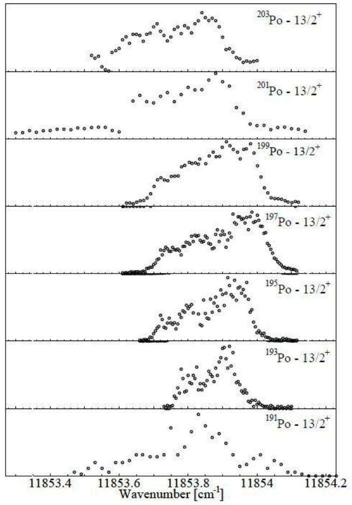
IS456: Timeline











Phase 0: 2006
- First laser ionization tests
- Saturation of the optical transitions
- Yields of $^{193-204}$Po

Phase 1: 2007
- Simultaneous GLM / CA0 beams
- Windmill: $^{193-199}$Po
- Tape station: $^{199-200,202,204}$Po

Phase 2: 2009
- Repeat of key measurements
- Faraday cup: $^{206,208-210}$Po
- Pseudo offline: ^{211g}Po
- Not using GLM to reach ^{216,218}Po
- Extra tape station: $^{201-203}$Po
- Extreme sensitivity: ^{191}Po

Phase 3: 2012
- LIST test
- Proof-of-principle measurements
- HFS: ^{217}Po
- Alpha decay: ^{219}Po

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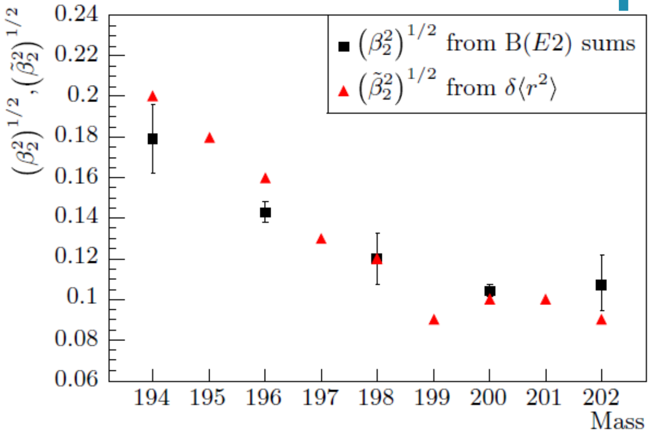
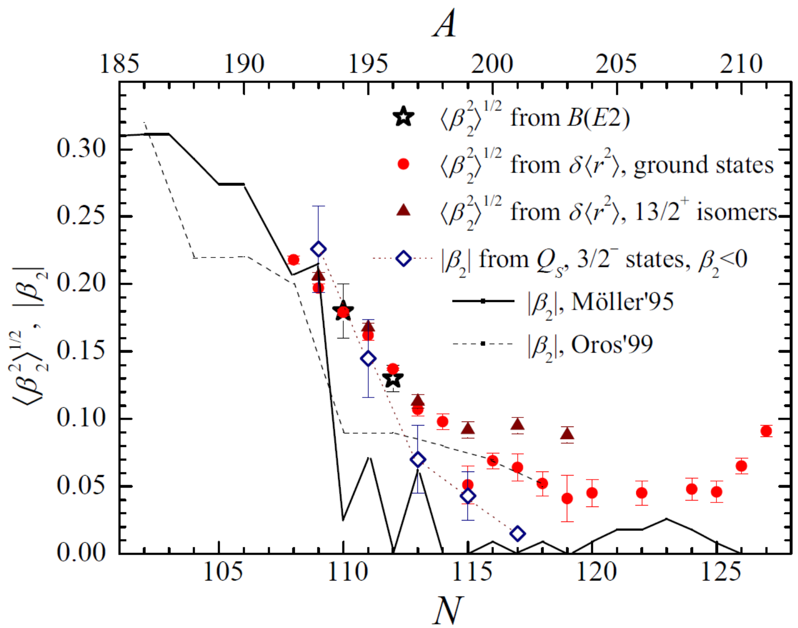
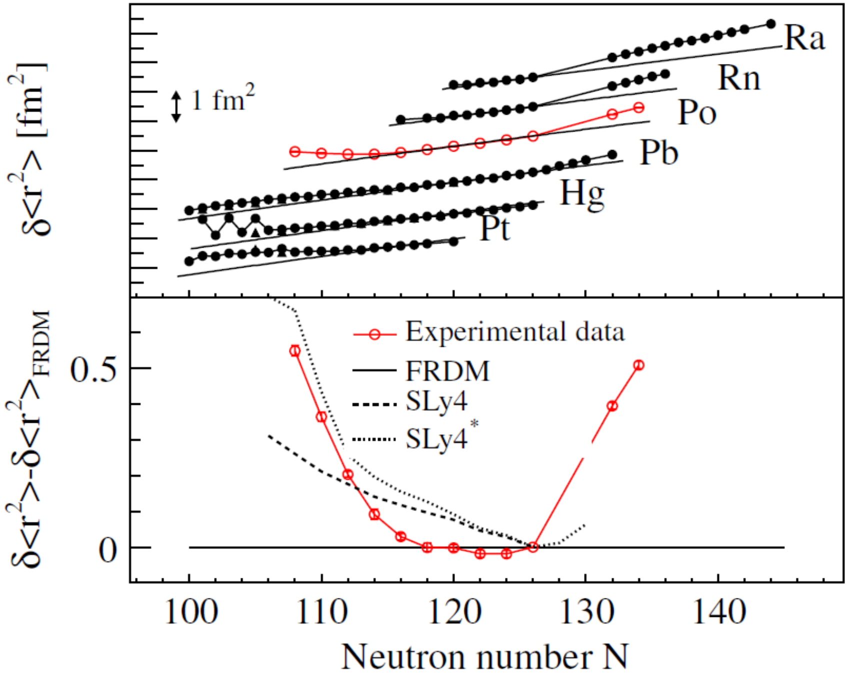
IS456: Shape coexistence near ^{186}Pb



Somewhat unexpected picture where the polonium isotopes depart steadily from sphericity, in contrast to how mercury staggers.

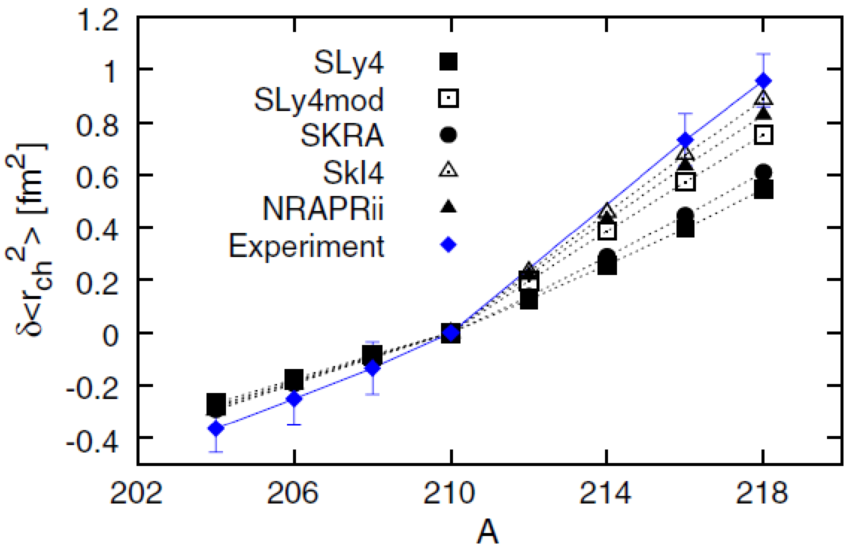


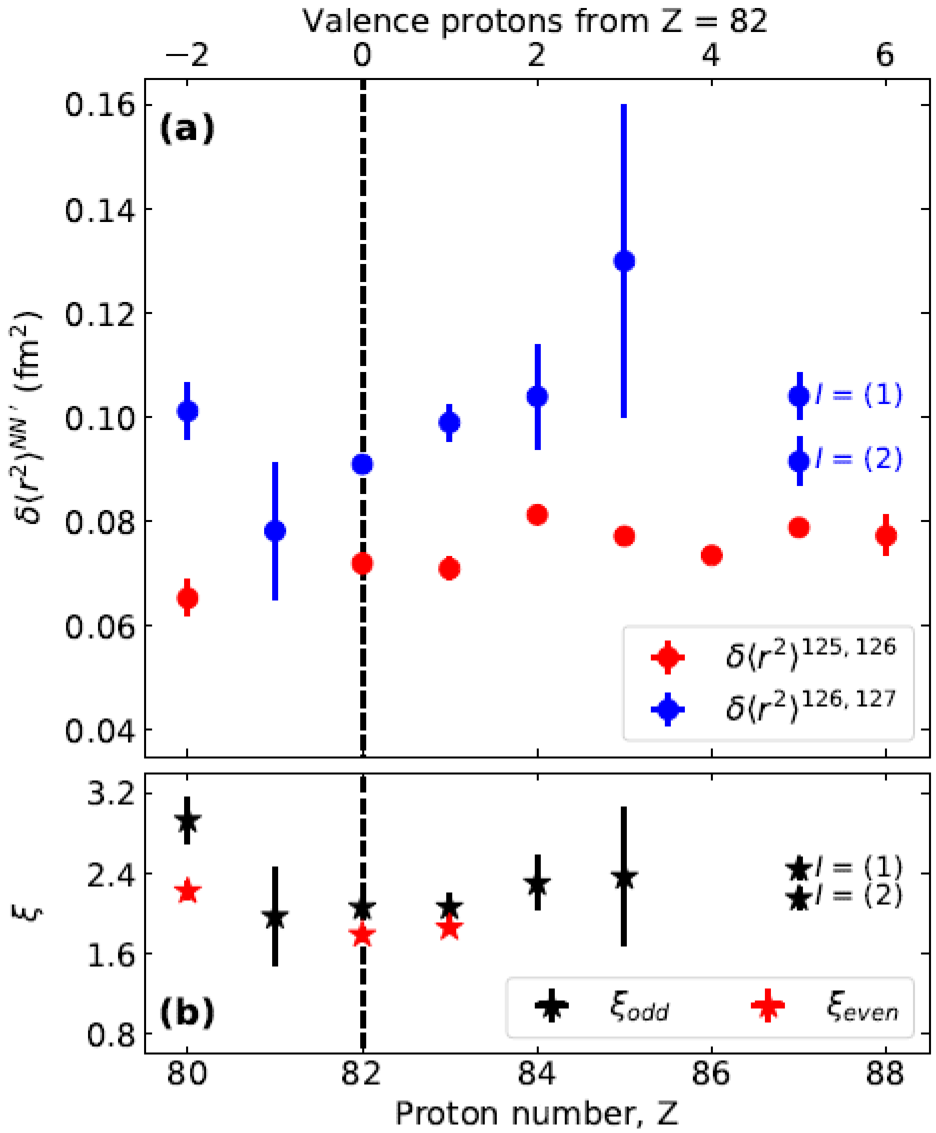


All observables are in agreement: dr2, moments from hfs, lifetime measurements and CoulEx.

*T.E. Cocolios et al, Physical Review Letters **106** (2011) 052503.*
*M.D. Seliverstov et al, Physical Review C **89** (2014) 034323.*
*N. Kesteloot et al, Physical Review C **92** (2015) 054301.*

IS456: Kink at N=126





The kink at the shell closure is not in itself a surprise, however its reproduction by nuclear theory remains a challenge, as much as its experimental investigation.

*P.M. Goddard, P.D. Stevenson and A. Rios, Physical Review Letters **110** (2013) 032503.*
*G.J. Farooq-Smith et al, PRC **94** (2016) 054305 & PhD Thesis (2019) KU Leuven.*
*& picture adapted from A.E. Barzakh et al, Physical Review C **97** (2018) 014322.*

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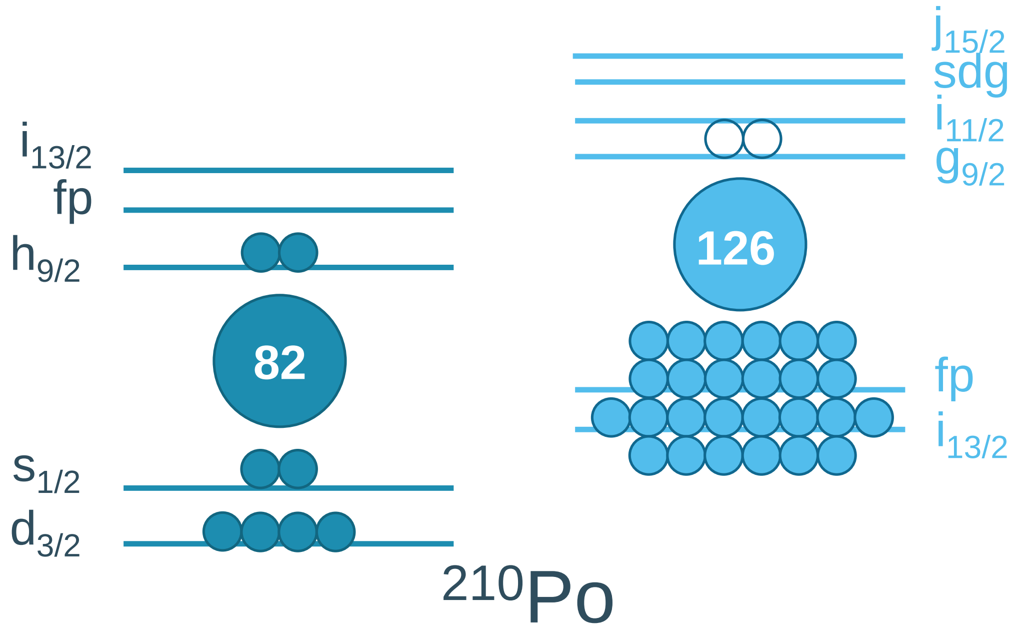
IS456: furthering the study around N=126



- Isotopes north-east of ^{208}Pb are all short-lived, down to μs and even ns. This has greatly limited the study of N=127-128 isotones, especially for the understanding of the kink in dr2.
- High-spin isomers exist in $^{211\text{-}212}Po$, which could give an insight into these features.
- Magnetic dipole moments will be studied to confirm the configuration.

Isotope	Half-life	Spin	Proton configuration	Neutron configuration
^{211g}Po	0.516 s	$9/2^+$	$(\pi h_{9/2})^2_{0+}$	$(\nu g_{9/2})$
^{211m}Po	25.2 s	$(25/2^+)$	$(\pi h_{9/2})^2_{8+}$	$(\nu g_{9/2})$
^{212g}Po	0.3 μs	0^+	$(\pi h_{9/2})^2_{0+}$	$(\nu g_{9/2})^2_{0+}$
^{212m}Po	45.1 s	(18^+)	$(\pi h_{9/2})^2_{8+}$	$(\nu g_{9/2})(\nu i_{11/2})_{10+}$

- The $(\nu i_{11/2})$ orbital is supposedly responsible for the kink and this could become more evident in the measurement of ^{212m}Po!

H. Nakada & T. Inakura, *Physical Review C* **91** (2015) 021302R.

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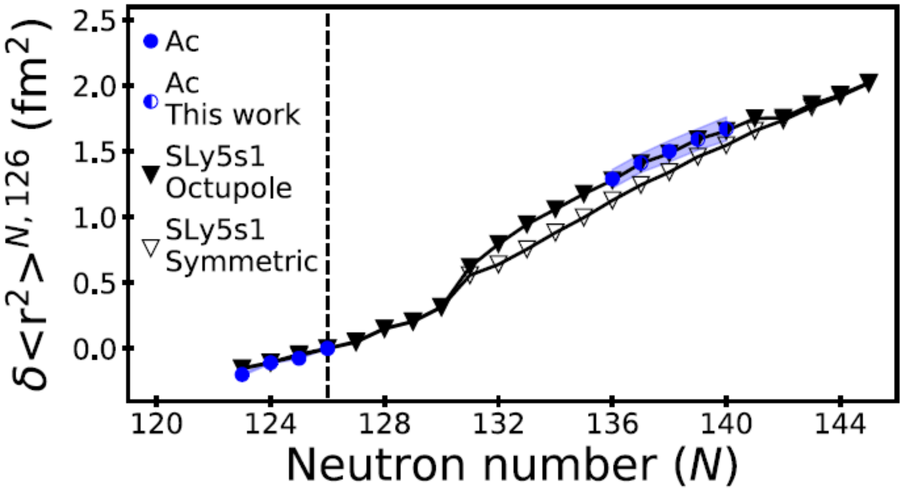
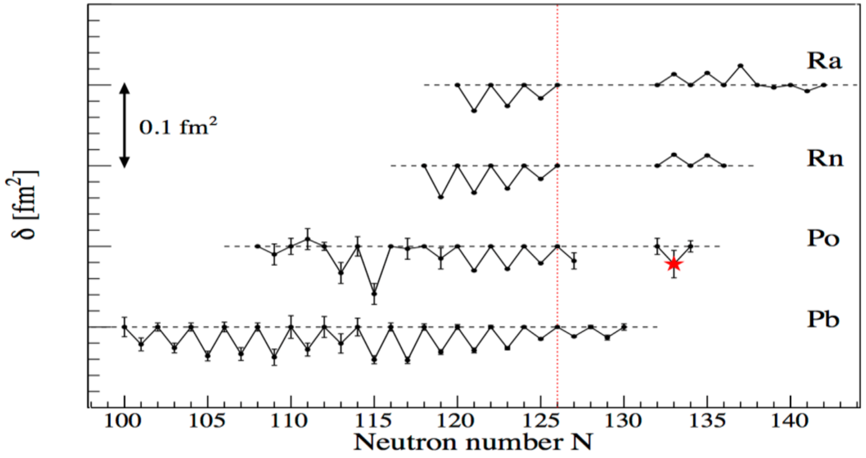
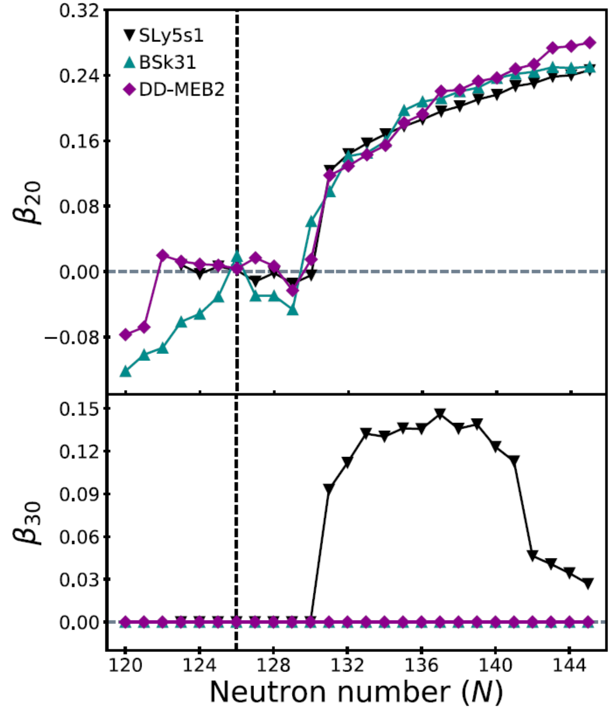
IS456: Beyond N=126





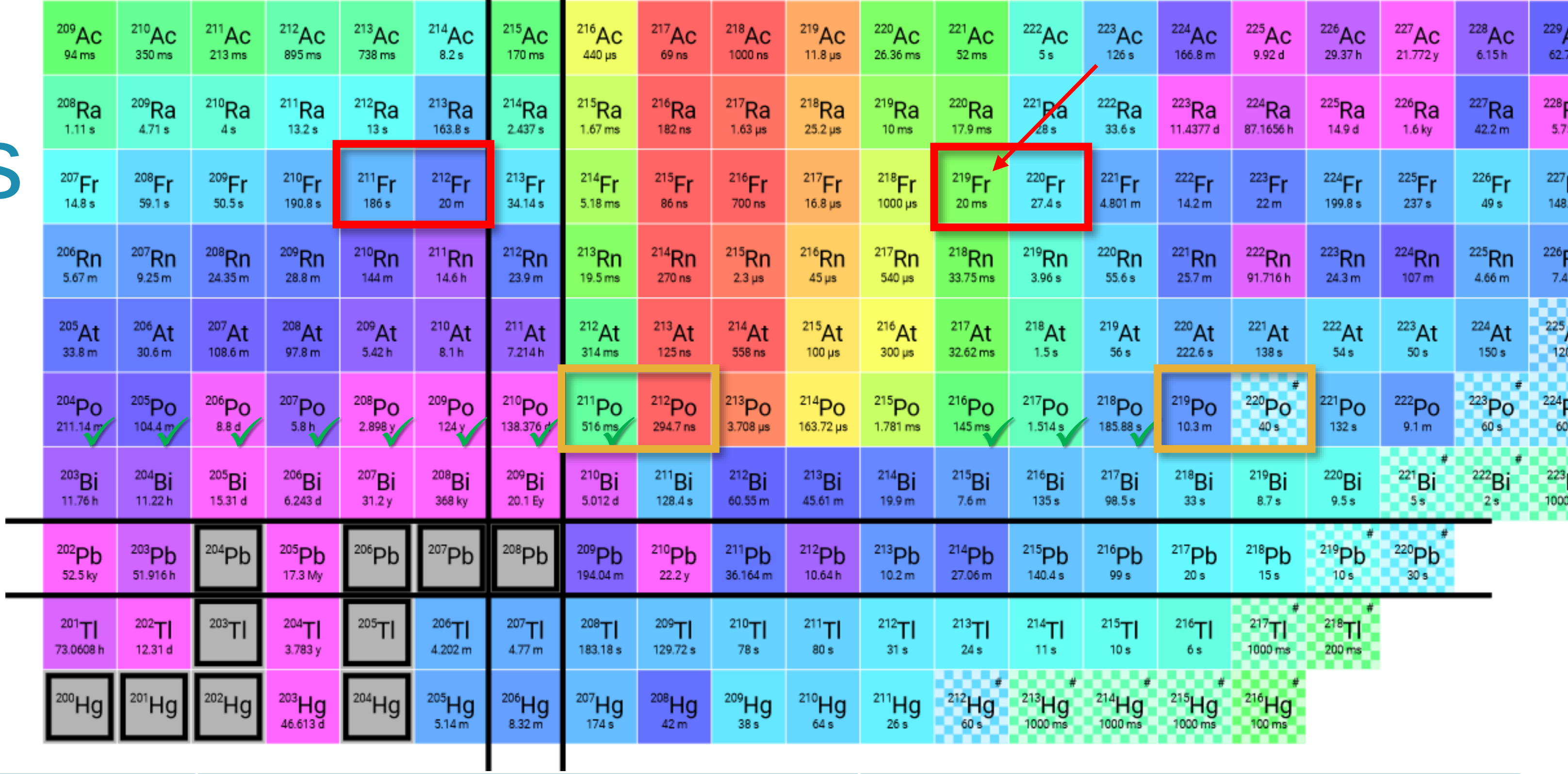
- Recent Energy Density Functionals calculations for Ac have highlighted how the trend in the dr2 is not a linear extrapolation from N=126, but rather undergoes a step in the vicinity of N=130.
- This behavior coincides with where the calculations suggest an onset of octupole deformation.

- Measurements of dr2 between N=126 and 132 are necessary to benchmark this with experimental observation.
- Odd-even staggering investigation in the region N=132-140 in polonium would also shed light on the possible correlations between the dr2 behavior and the shapes in this region.



*E. Verstraelen et al, Physical Review C **100** (2019) 044321.*
*D. Fink et al, Physical Review X **5** (2015) 011018.*

IS456: challenges



Isobaric contamination!

- * Yields estimated based on ABRABLA calculations
- ** Constant in-target feeding by ^{223}Ac with $T_{1/2}$ = 2 min

A	Polonium		Francium	
	$T_{1/2}$	Yield* [ions/μC]	$T_{1/2}$	Yield [ions/μC]
211	25.2 s	2 x 10^4	3 min	10^8
212	45.1 s	2 x 10^4	20 min	10^8
219	10.3 min	3 x 10^1	20 ms**	10^3
220	-	1 x 10^1	27.4 s	10^7

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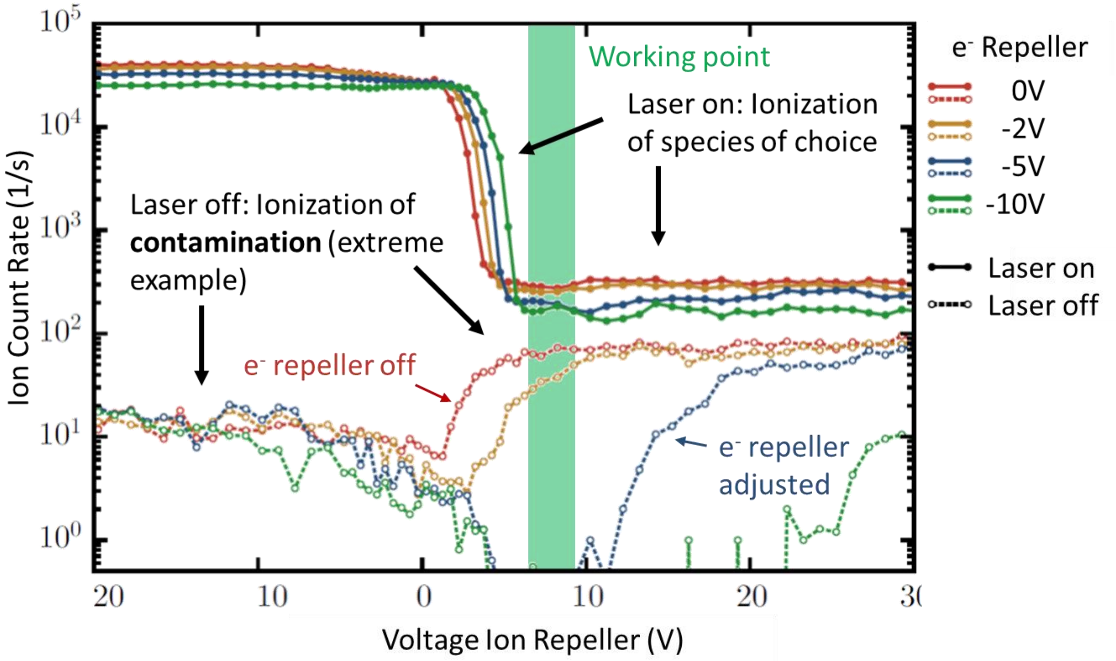
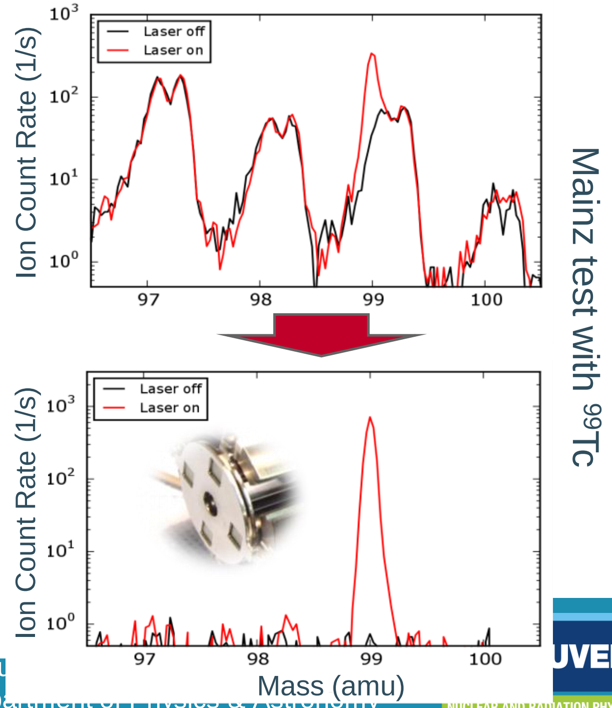
IS456: Solutions

LIST 2.0!

- 2012 attempt showed promise (e.g. hfs of ^{217}Po, first α decay spectroscopy of ^{219}Po) but suppression of ^{212}Fr was far inferior to that of ^{205}Fr.
- Electron impact ionization of decay products of radioactive material deposited on the LIST surfaces (namely from deposited isobaric Ra) is the reason.
- A new LIST has been designed in Mainz with a double repeller system to prevent surface ions AND electrons from entering the RFQ.
- The LIST 2.0 will be implemented as an ISOLDE standard ion source in the course of 2020 ready for the facility restart in 2021.

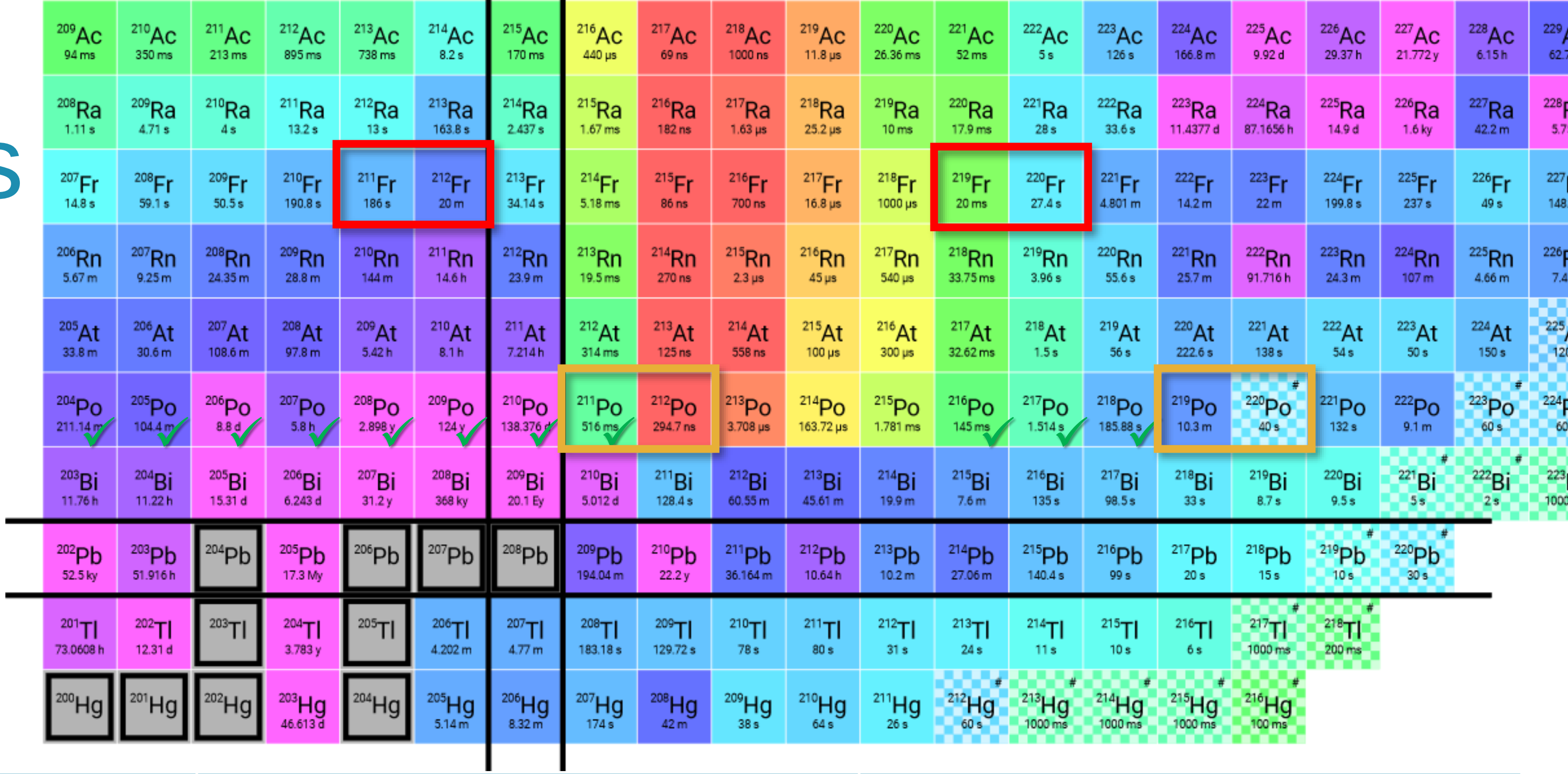




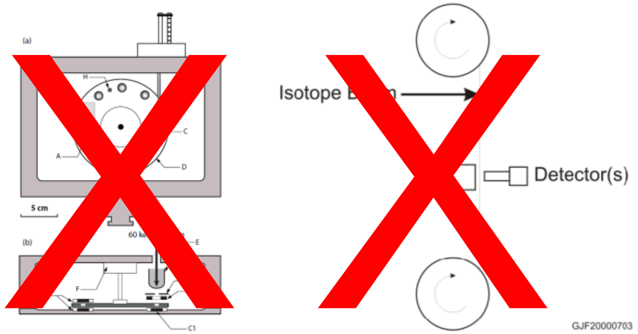
Reinhard Heinke starting at ISOLDE on 2 Dec 2019

M. Truemper, BSc Thesis (2015), Mainz.
R. Heinke, PhD Thesis (2019), Mainz.

IS456: challenges



Detection



- The Windmill is dead and buried and never to be seen again…
- FC is not an option for those beams
- $T_{1/2}$ in $^{219-220}$Po is not favorable for decay counting

A	Polonium		Francium	
	$T_{1/2}$	Decay mode	$T_{1/2}$	Decay mode
211m	25.2 s	>99.9% α	3 min	87% α / 13% β
212m	45.1 s	>99.9% α	20 min	43% α / 57% β
219	10.3 min	28% α / 72% β	20 ms	α
220	-	-	27.4 s	>99.6% α

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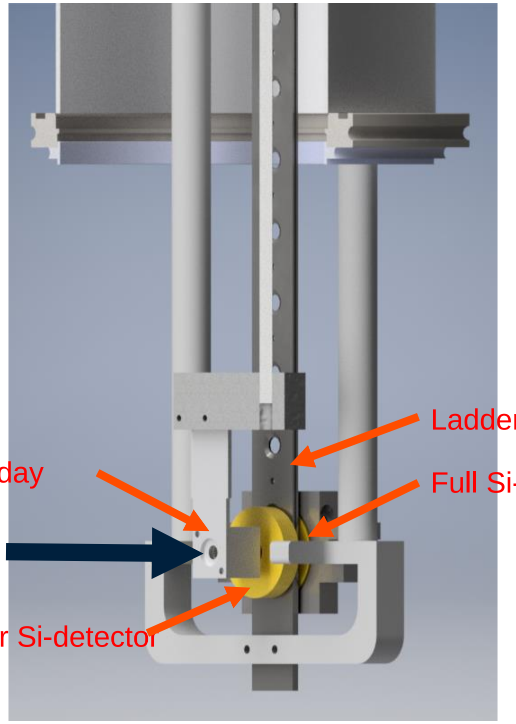
IS456: Solutions

- IDS is equipped with a moving tape to remove the long-lived activity, perfect for $^{219,220}Po$.
- The implantation point is surrounded by charged particle detectors and γ-ray detectors for a comprehensive measurement of the decay of the implanted activity.
- Full synchronization with RILIS is established for scanning.

New α chamber & IDS



- A replacement for the Windmill has been developed and tested for IS637.
- It consists of a similar Si sandwich around a ladder with 10 C foils.
- An integrated FC is available for beam transport / tuning.

Free decay spectroscopy data acquired in the process

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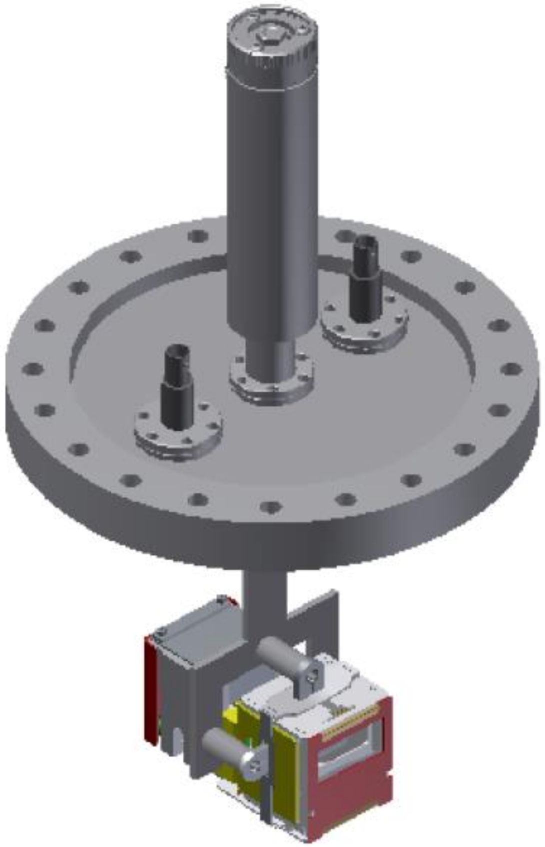
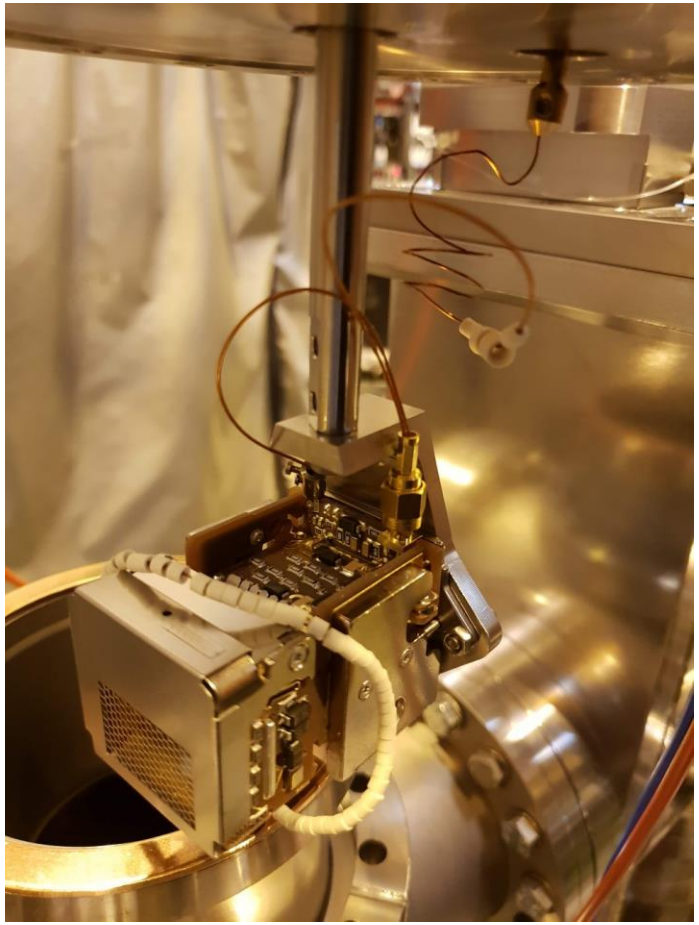
IS456: Solutions

Single-ion counting

- Single-ion counting capability is currently available in the ISOLDE Central Beam Line.
- This would allow to measure long-lived isotopes like $^{219\text{-}220}Po$ quickly and efficiently.

NOT for $^{208\text{-}210}Po$





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IS456: Shifts breakdown

	Isotope	Number of shifts
LIST test		2
Reference measurements	$^{196,208\text{-}210}Po$	2.5
HFS & IS	^{211m}Po	2
HFS & IS	^{212m}Po	2
HFS, IS & decay	^{219}Po	7
HFS, IS & decay	^{220}Po	7
	TOTAL	**22.5**

- The IS456 scientific case remains current and unchallenged
  - No dr2 data on N=128, Z>83
  - No new information on the configuration of the high-spin isomers
  - New insight into the dr2 for N=130-140 requires new experimental data
  - No new decay data on $^{219,220}Po$
- Main challenges have been addressed
  - New LIST with double repeller to be fully integrated at ISOLDE
  - New detection systems: α chamber, IDS, single-ion counting

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Extra slides

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IS456: Collaboration

E. Ahmed, A. Algora, B. Andel, A.N. Andreyev, S. Antalic, A.E. Barzakh, B. Bastin, M. Bissell, M. Borge, K. Chrysalidis, T.E. Cocolios, B. Cooper, J. Cubiss, H. De Witte, K. Dockx, D.V. Fedorov, V.N. Fedosseev, R. Ferrer, K.T. Flanagan, S. Franchoo, L. Fraile, H. Fynbo, L. Ghys, L.J. Harkness-Brennan, R. Heinke, D.S. Judson, J. Konki, U. Koster, I. Lazarus, N. Lecesne, R. Lica, N. Marginean, B.A. Marsh, C. Mihai, P.L. Molkanov, E. Nacher, A. Negret, J. Ojala, R.D. Page, J. Pakarinen, A. Perea, H. Perrett, L. Popescu, V. Pucknell, C. Ricketts, S.R. Rothe, H. Savajols, M.D. Seliverstov, S. Sels, C. Sotty, M. Stryjczyk, O. Tengblad, J. Van de Walle, P. Van den Bergh, P. Van Duppen, M. Vandebrouck, V. Vedia, M. Venhart, S. Vinals, R. Wadsworth, N. Warr, K.D.A. Wendt, S.G. Zemlyanoy

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IS456: scientific output

- 6 papers & 5 conference proceedings with >250 citations
  - 2 technical conference proceedings (EMIS NIMB) + 3 conference proceedings with results
  - 1x EPJA, JPG, PLB, PRA, PRL, PRX
- 3 theses
  - 1 MSc
    - Wim Dexters, KU Leuven 2010
  - 2 PhD
    - Thomas Cocolios, KU Leuven 2010
    - Daniel Fink, Heidelberg 2015

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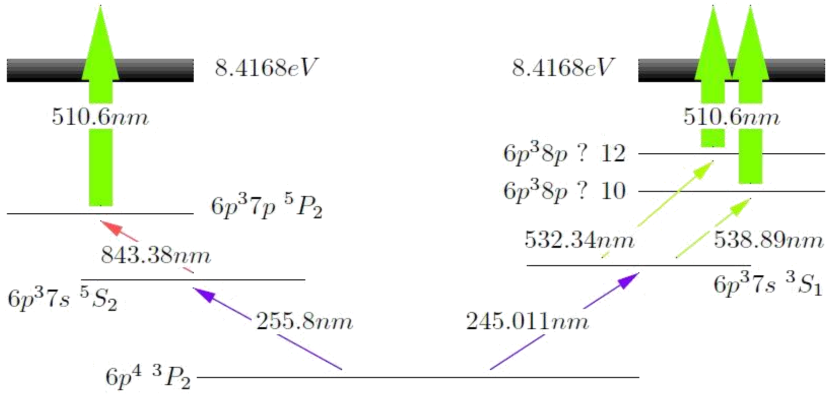
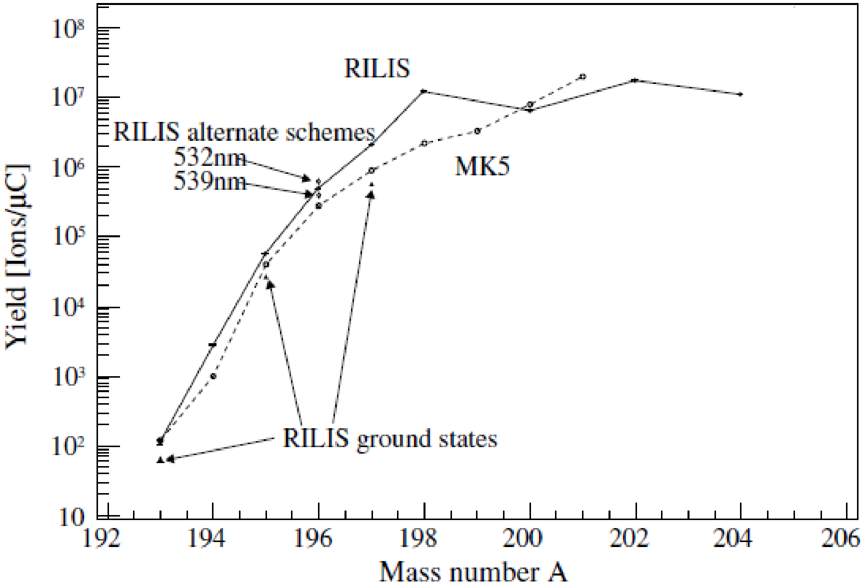
IS456: Timeline





Phase 0: 2006

- First laser ionization tests
- Saturation of the optical transitions
- Yields of $^{193\text{-}204}Po$

T.E. Cocolios et al, NIMB ***266*** *(2008) 4403-4406.*

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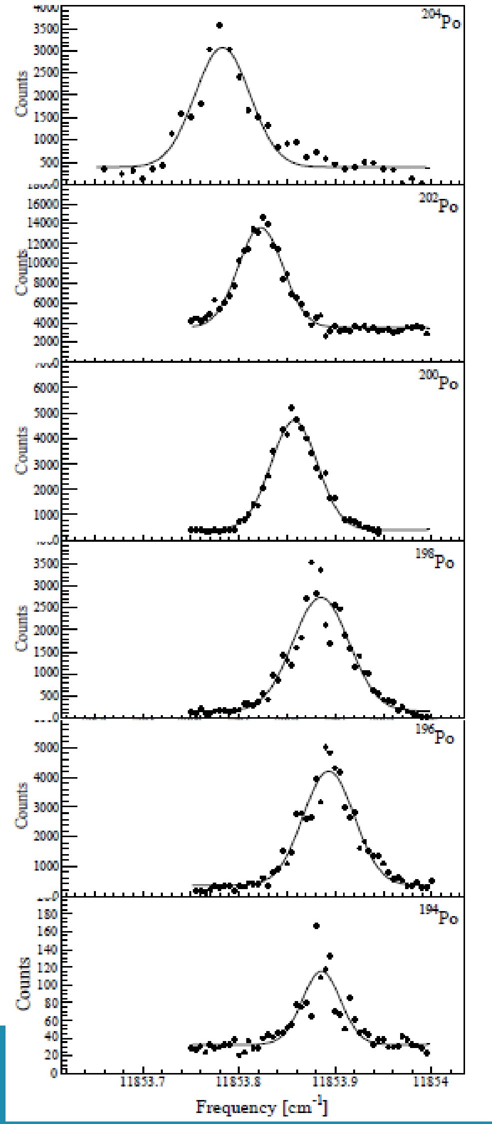

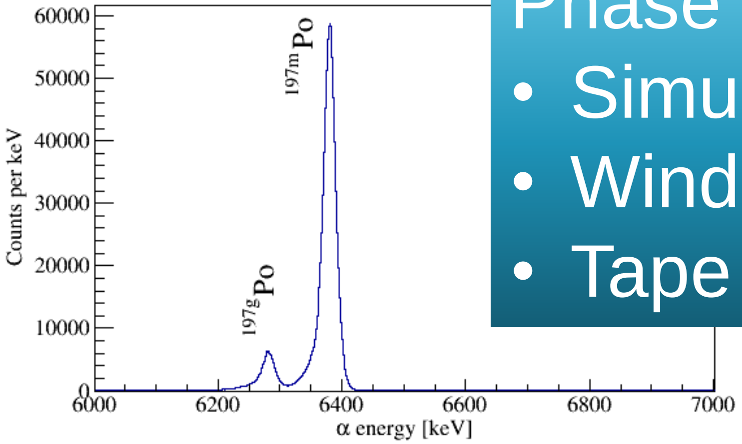

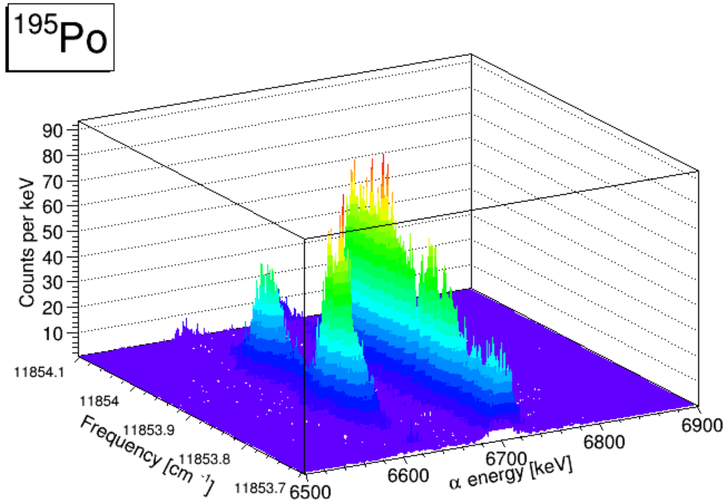

Too little overlap with literature data to extract the observables of interest!

IS456: Timeline

Phase 0: 2006
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beams

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Phase 2: 2009
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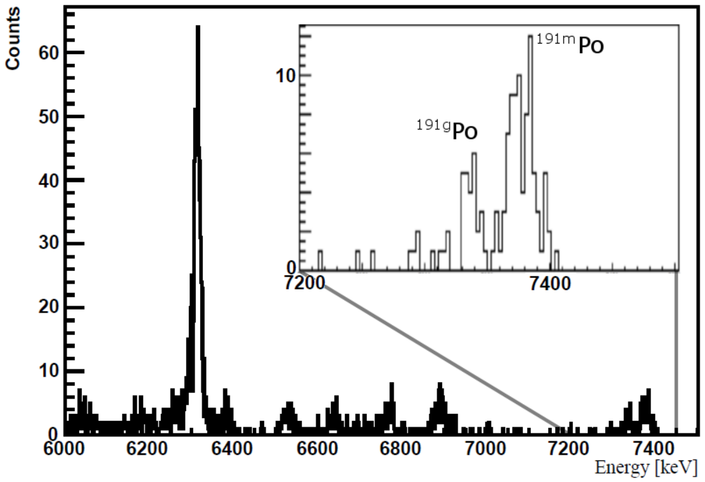
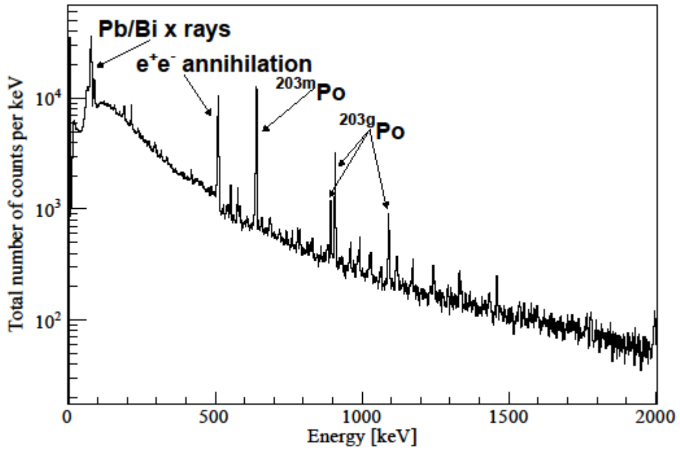
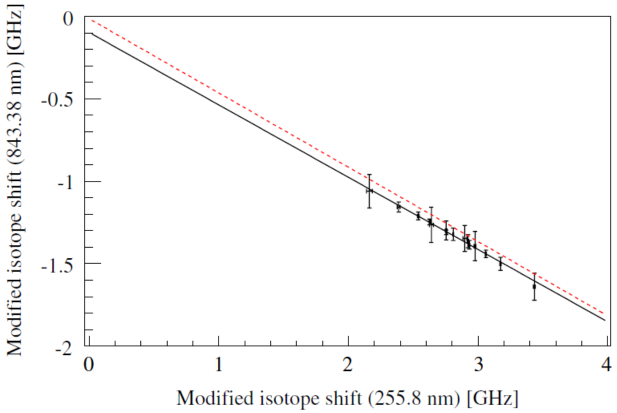


^{203}Po





Isobaric Fr/Ra was the limiting factor in the neutron-rich isotopes

*T.E. Cocolios et al, Physical Review Letters **106** (2011) 052503.*
*B. Cheal, T.E. Cocolios, S. Fritzsche, Physical Review A **86** (2012) 042501.*

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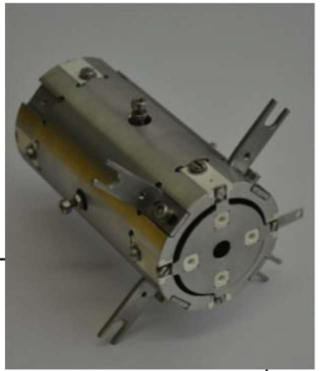

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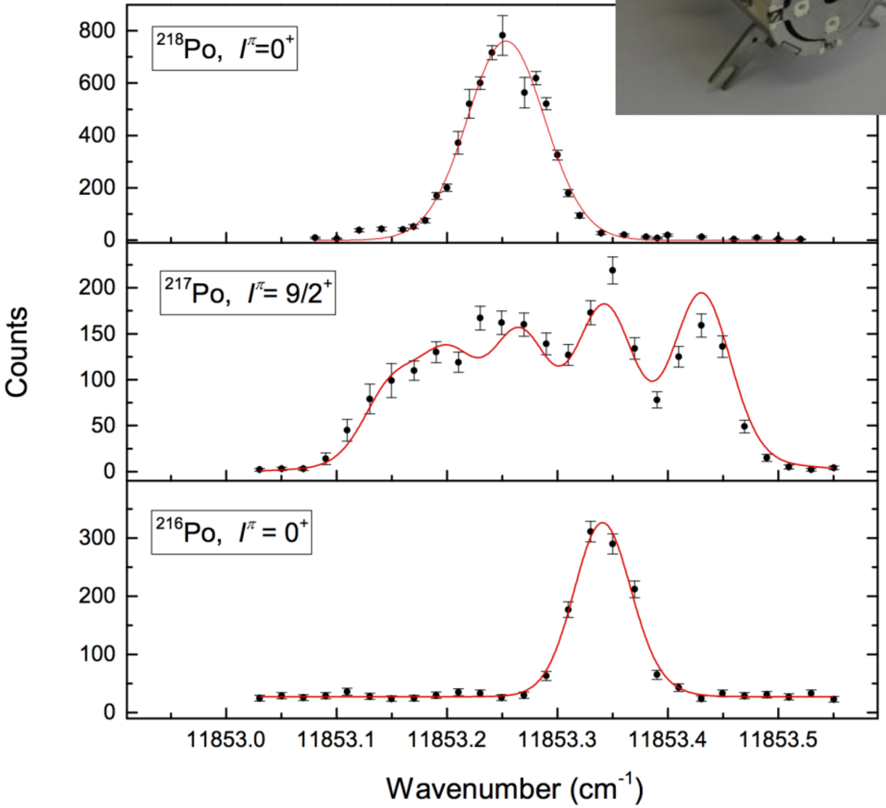

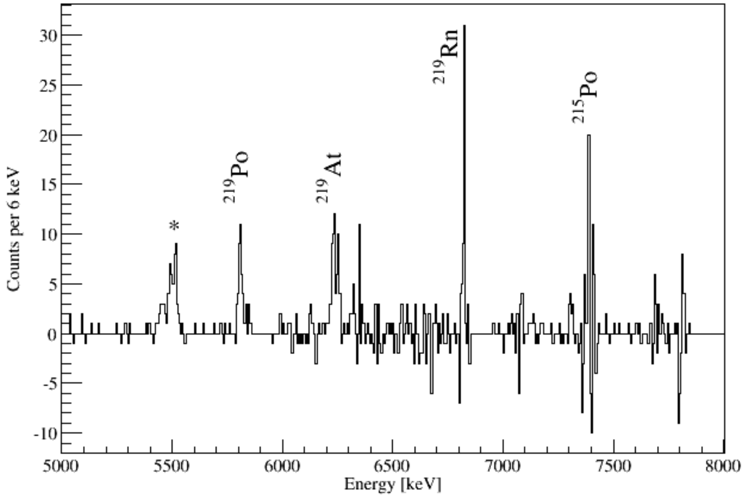

*D. Fink et al, NIMB **317** (2013) 417-421.*
*D. Fink et al, Physical Review X **5** (2015) 011018.*

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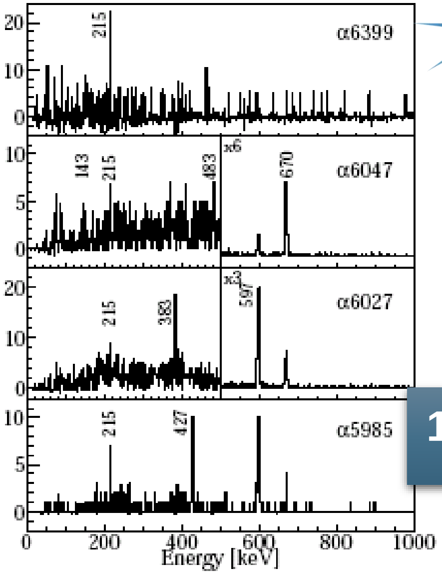
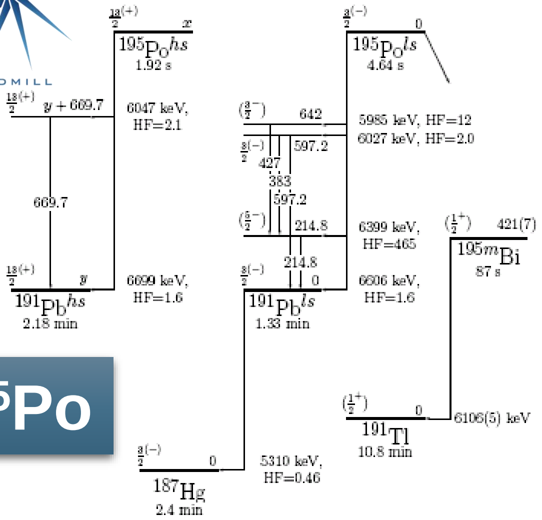
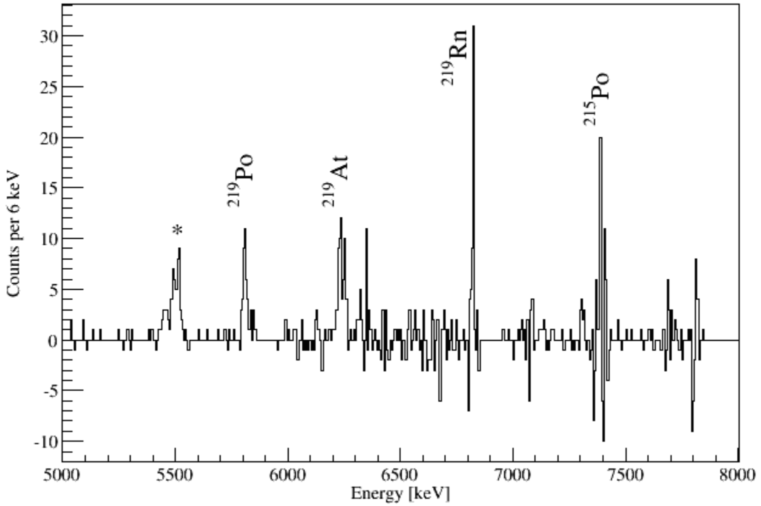
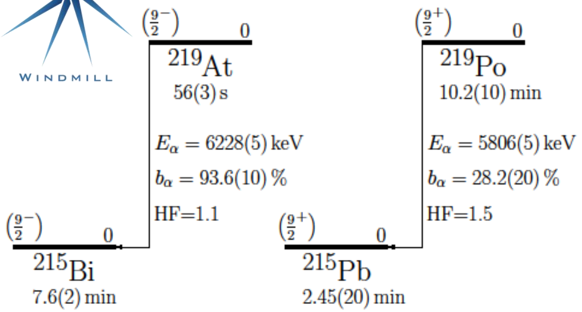
IS456: decay spectroscopy results



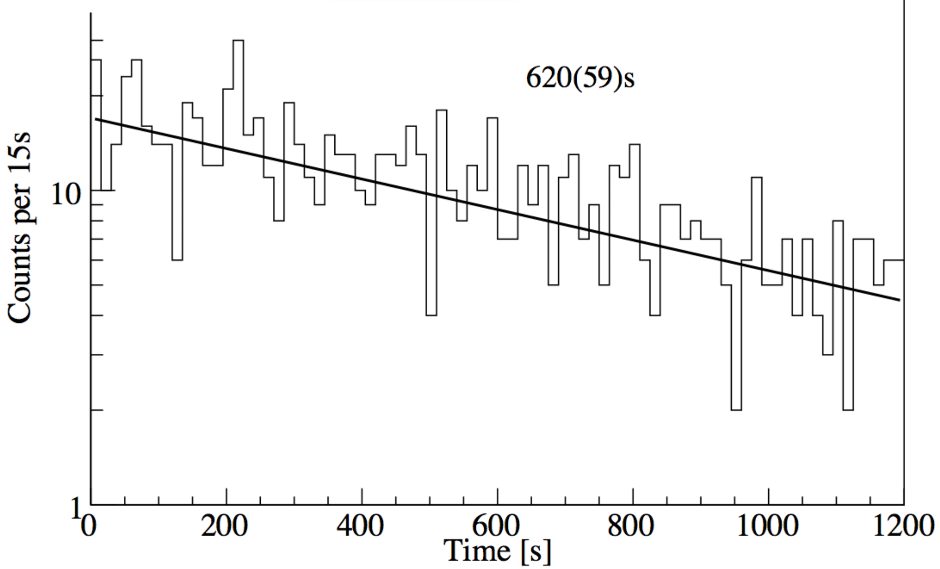


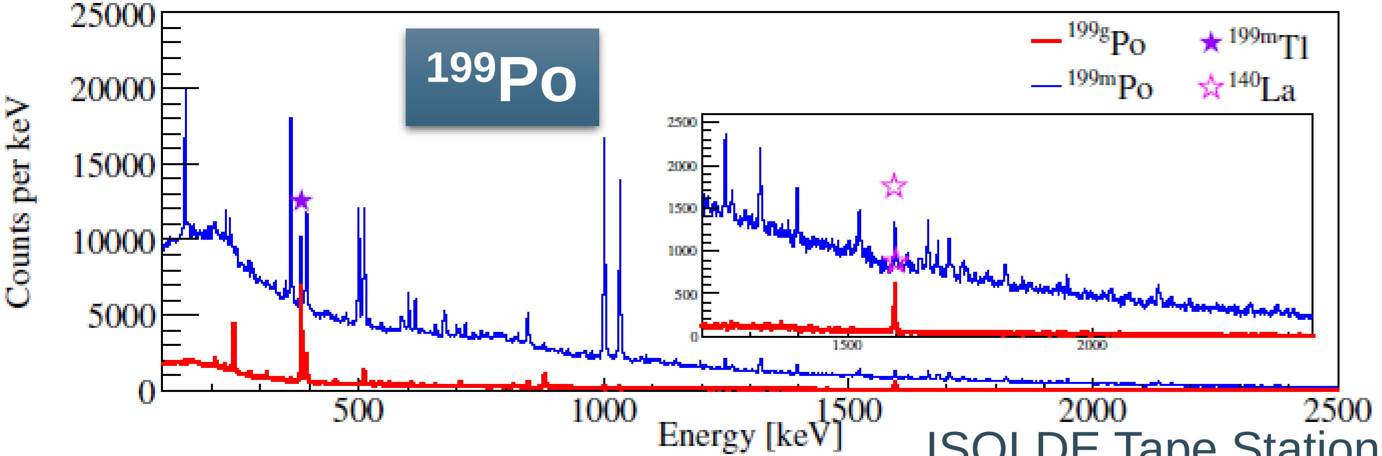
195Po





219Po





199Po

ISOLDE Tape Station

*T.E. Cocolios et al, JPG **37** (2010) 125103.*
*T.E. Cocolios et al, JPCS **381** (2012) 012072.*
*D. Fink et al, Physical Review X **5** (2015) 011018.*

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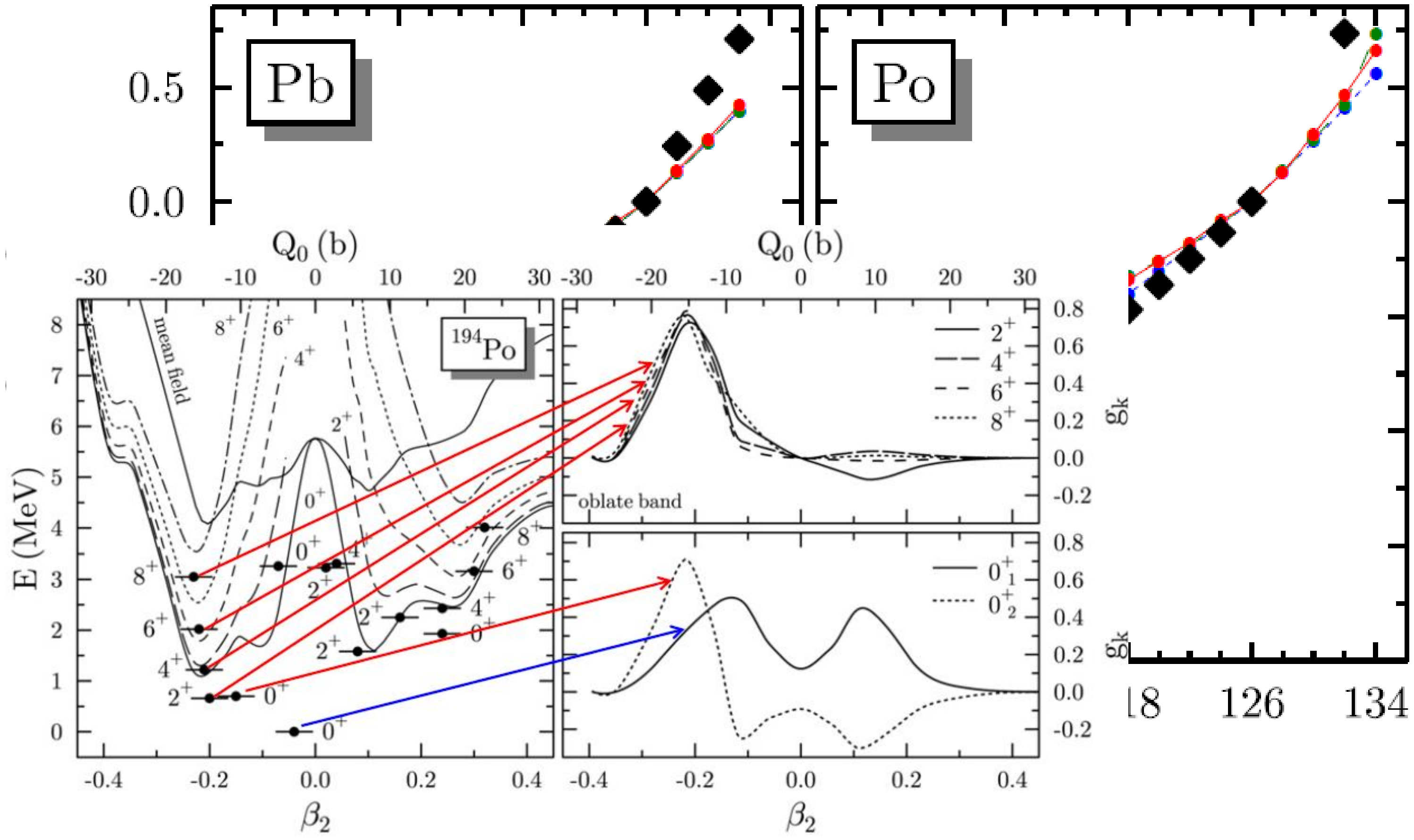
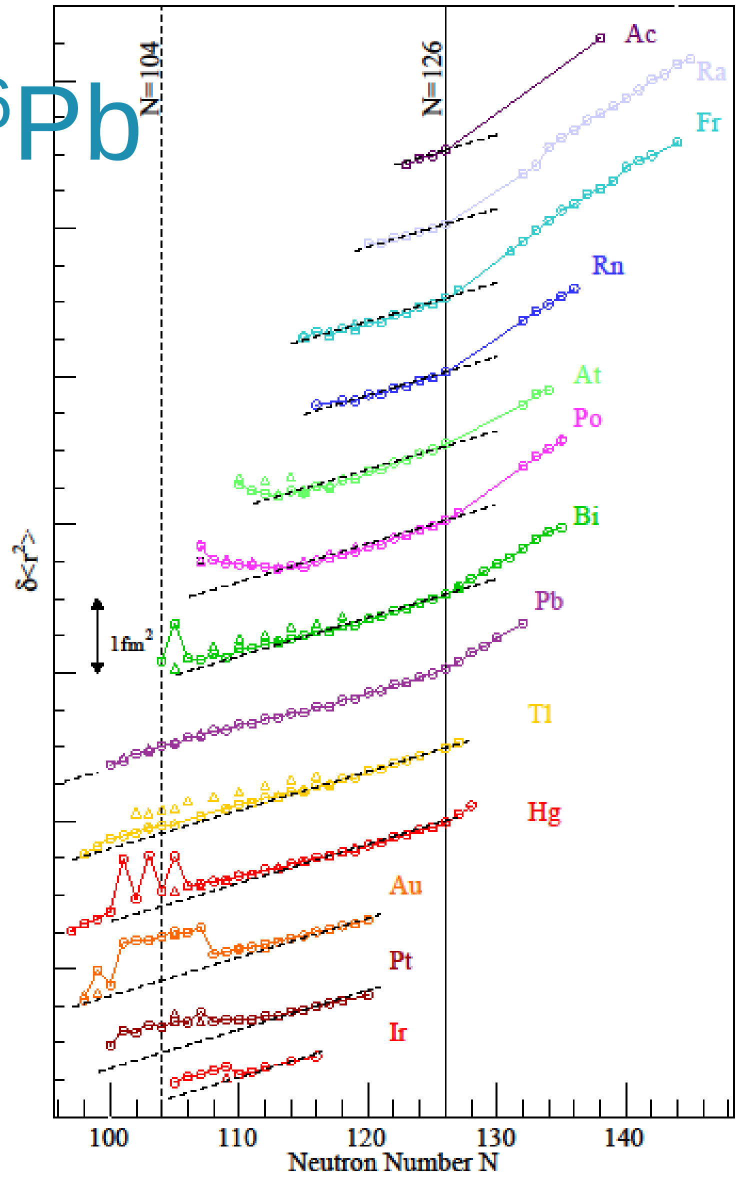
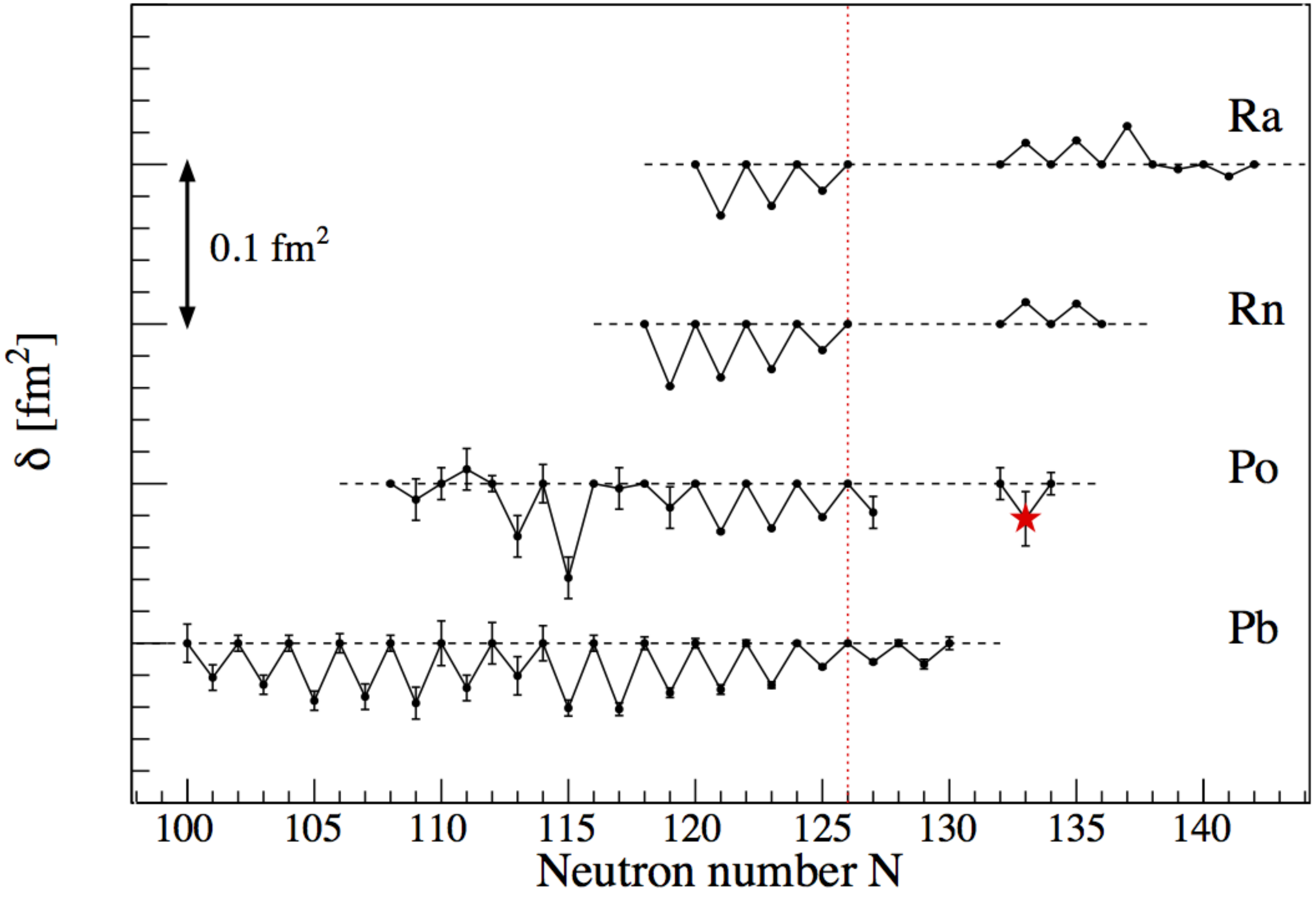
IS456: Shape coexistence near ^{186}Pb





M. Bender, private communication, adapted from M. Bender et al, PRC ***73*** *(2006) 034322.*
T. Grahn et al, Nuclear Physics A ***801*** *(2008) 83-100.*
T.E. Cocolios, Hyperfine Interactions ***238*** *(2017) 16.*

IS456: odd-even staggering



The reversal of the odd-even staggering in dr2 has been observed in the region also known for its reflection asymmetry. As polonium is located at the low-Z edge of this region, investigating its charge distribution is crucial to further understand the link between these two properties.

*D. Fink et al, Physical Review X **5** (2015) 011018.*

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IS456: Publications

- Main scientific publications

1. T.E. Cocolios et al, *Structure of 191Pb from α- and β-decay spectroscopy*, Journal of Physics G **37** (2010) 125103.
2. B. Cheal, T.E. Cocolios, T.E. Cocolios, W. Dexters, M.D. Seliverstov et al, *Early onset of ground state deformation in neutron deficient polonium isotopes*, Physical Review Letters **106** (2011) 052503.
3. S. Fritzsche, *Laser spectroscopy of radioactive isotopes: Role and limitations of accurate isotope-shift calculations*, Physical Review A **86** (2012) 042501.
4. M.D. Seliverstov, T.E. Cocolios, W. Dexters et al, *Charge radii of odd-A $^{191-211}$Po isotopes*, Physics Letters B **719** (2013) 362-366.
5. M.D. Seliverstov, T.E. Cocolios, W. Dexters et al, *Electromagnetic moments of odd-A $^{191-203,211}$Po isotopes*, Physical Review C **89** (2014) 034323.
6. D.A. Fink, T.E. Cocolios et al, *In-source laser spectroscopy with the Laser Ion Source and Trap: first direct study of the ground-state properties of ^{217,219}Po*, Physical Review X **5** (2015) 011018.

- Conference proceedings

1. T.E. Cocolios, B.A. Marsh et al, *Resonant laser ionization of polonium at RILIS-ISOLDE for the study of ground- and isomer-state properties*, NIMB **266** (2008) 4403-4406, Proceedings to the EMIS Conference 2007 in Deauville, France.
2. T.E. Cocolios et al, *Early onset of deformation in the neutron-deficient polonium isotopes (decay spectroscopy of ^{199}Po)*, Journal of Physics: Conference Series **381** (2012) 012072.
3. D.A. Fink, S.D. Richter et al, *First application of the Laser Ion Source and Trap (LIST) for on-line experiments at ISOLDE*, NIMB **317** (2013) 417-421, Proceedings to the EMIS Conference 2012 in Matsue, Japan.
4. T.E. Cocolios, *Shape coexistence in the lead region from a ground-state perspective*, xxx, (2015) page 43-49, Proceedings to the ISTROS Conference 2013 in Častá-Papiernička, Slovakia.
5. T.E. Cocolios, *A new perspective on charge radii around Z=82*, Hyperfine Interactions **238** (2017) 16, Proceedings of the 10th International Workshop on Application of Lasers and Storage Devices in Atomic Nuclei Research: “Recent Achievements and Future Prospects” (LASER 2016), Poznan, Poland