Nuclear and laser spectroscopy study of the neutron-rich ^{212,213,215,216,217,219,220}Bi isotopes with LIST

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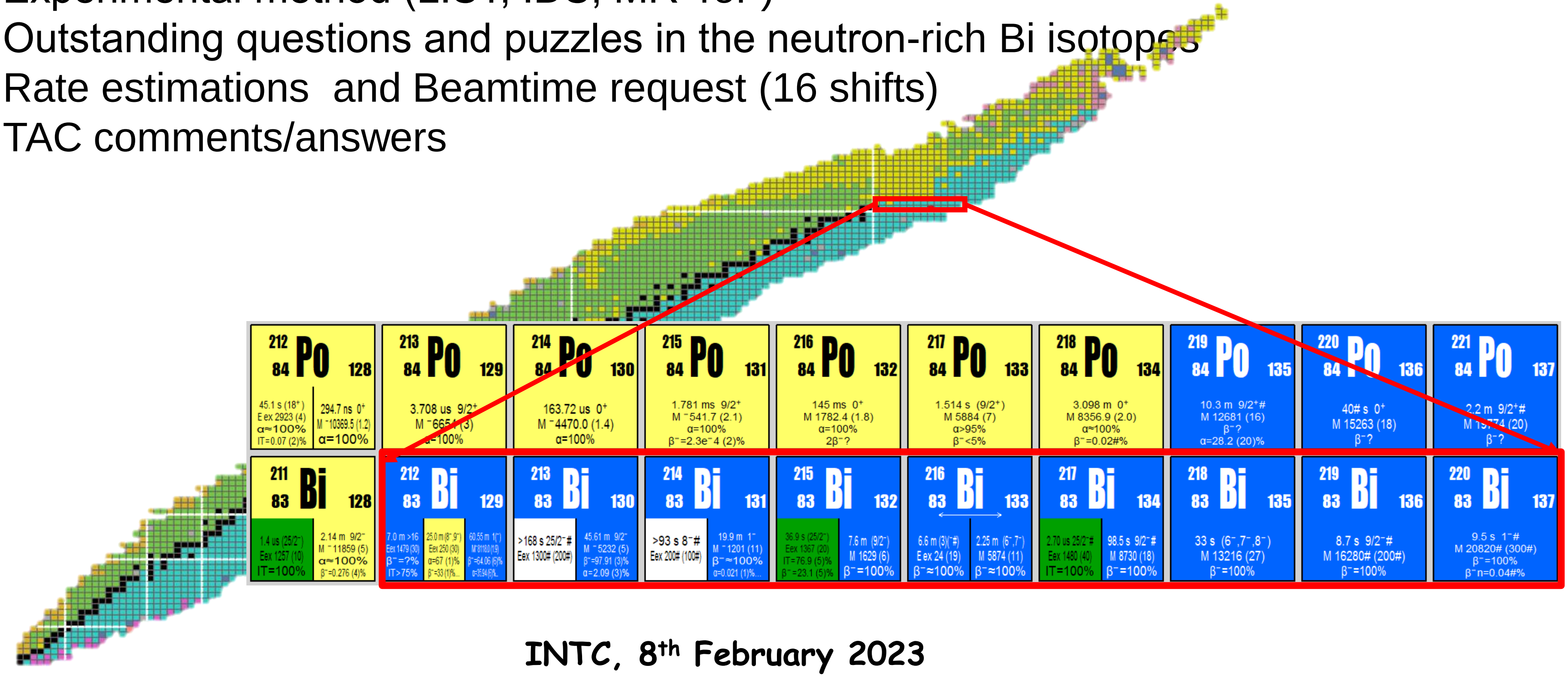
on behalf of York-Gatchina-Leuven-Bratislava-Bucharest...
+IDS-RILIS-ISOLTRAP Collaboration

Contents

- Previous Bi studies by our collaboration (IS608, IS650)
- Experimental method (LIST, IDS, MR-ToF)
- Outstanding questions and puzzles in the neutron-rich Bi isotopes
- Rate estimations and Beamtime request (16 shifts)
- TAC comments/answers



$^{212}_{84}$Po 128 45.1 s (18^+) E ex 2923 (4) α≈100% IT=0.07 (2)% 294.7 ns 0^+ M $^-$10369.5 (1.2) α=100%	$^{213}_{84}$Po 129 3.708 us $9/2^+$ M $^-$6654 (3) α=100%	$^{214}_{84}$Po 130 163.72 us 0^+ M $^-$4470.0 (1.4) α=100%	$^{215}_{84}$Po 131 1.781 ms $9/2^+$ M $^-$541.7 (2.1) α=100% β^-=2.3e$^-$4 (2)%	$^{216}_{84}$Po 132 145 ms 0^+ M 1782.4 (1.8) α=100% 2β^-?	$^{217}_{84}$Po 133 1.514 s ($9/2^+$) M 5884 (7) α>95% β^-<5%	$^{218}_{84}$Po 134 3.098 m 0^+ M 8356.9 (2.0) α≈100% β^-=0.02#%	$^{219}_{84}$Po 135 10.3 m $9/2^+$# M 12681 (16) β^-? α=28.2 (20)%	$^{220}_{84}$Po 136 40# s 0^+ M 15263 (18) β^-?	$^{221}_{84}$Po 137 2.2 m $9/2^+$# M 19774 (20) β^-?
$^{211}_{83}$Bi 128 1.4 us ($25/2^-$) Eex 1257 (10) IT=100% 2.14 m $9/2^-$ M $^-$11859 (5) α≈100% β^-=0.276 (4)%	$^{212}_{83}$Bi 129 7.0 m >16 Eex 1479 (30) β^-=?% IT>75% 25.0 m (8^-,9^-) Eex 250 (30) α=67 (1)% β^-=33 (1)%... 60.55 m 1($^-$) M $^-$8118.0 (1.9) β^-=64.06 (6)% α=35.94 (6)%...	$^{213}_{83}$Bi 130 >168 s $25/2^-$# Eex 1300# (200#) 45.61 m $9/2^-$ M $^-$5232 (5) β^-=97.91 (3)% α=2.09 (3)%	$^{214}_{83}$Bi 131 >93 s 8^-# Eex 200# (100#) 19.9 m 1^- M $^-$1201 (11) β^-≈100% α=0.021 (1)%...	$^{215}_{83}$Bi 132 36.9 s ($25/2^-$) Eex 1367 (20) IT=76.9 (5)% β^-=23.1 (5)% 7.6 m ($9/2^-$) M 1629 (6) β^-=100%	$^{216}_{83}$Bi 133 6.6 m (3)($^-$#) E ex 24 (19) β^-≈100% 2.25 m (6^-,7^-) M 5874 (11) β^-≈100%	$^{217}_{83}$Bi 134 2.70 us $25/2^-$# Eex 1480 (40) IT=100% 98.5 s $9/2^-$# M 8730 (18) β^-=100%	$^{218}_{83}$Bi 135 33 s (6^-,7^-,8^-) M 13216 (27) β^-=100%	$^{219}_{83}$Bi 136 8.7 s $9/2^-$# M 16280# (200#) β^-=100%	$^{220}_{83}$Bi 137 9.5 s 1^-# M 20820# (300#) β^-=100% β^-n=0.04#%

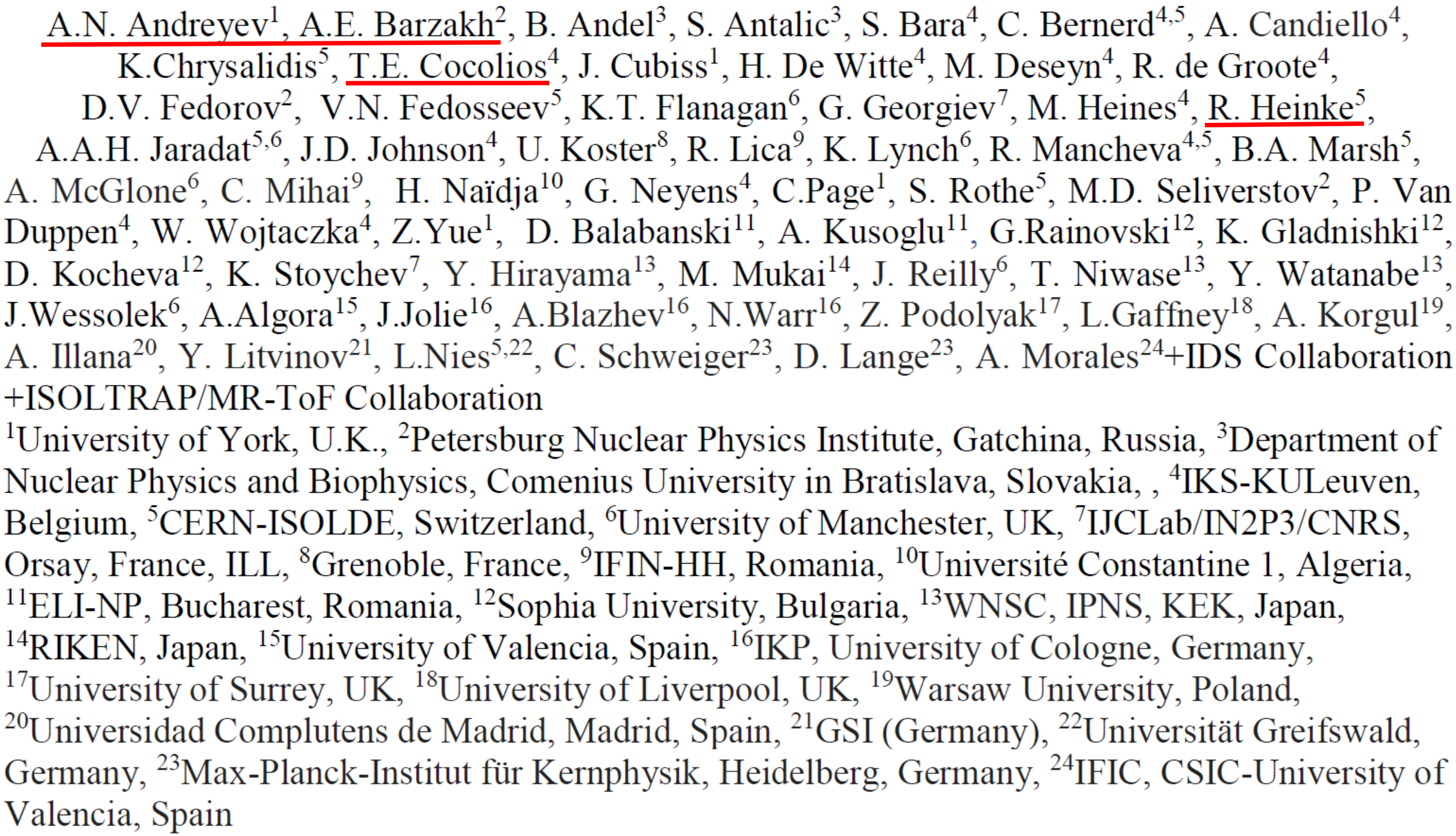
INTC, 8th February 2023

Why LIST? -Fr contamination at some masses

- Long-lived, strongly-produced Fr contaminants only at A=212,213 and 220
- At all other masses, Fr's are short-lived (ms/sub-ms), can be suppressed by the beam gate

^{213}Ac	^{214}Ac	^{215}Ac 170 ms	^{216}Ac 330 µs	^{217}Ac 69 ns	^{218}Ac 1.1 µs	^{219}Ac	^{220}Ac	^{221}Ac	^{222}Ac	^{223}Ac	^{224}Ac	^{225}Ac	^{226}Ac	^{227}Ac
^{212}Ra	^{213}Ra	^{214}Ra	^{215}Ra 1.6 ms	^{216}Ra 180 ns	^{217}Ra 1.6 µs	^{218}Ra 26 µs	^{219}Ra	^{220}Ra	^{221}Ra	^{222}Ra	^{223}Ra	^{224}Ra	^{225}Ra	^{226}Ra
^{211}Fr	^{212}Fr 20 m	^{213}Fr 24 s	^{214}Fr 5 ms	^{215}Fr 86 ns	^{216}Fr 700 ns	^{217}Fr 22 µs	^{218}Fr 1 ms	^{219}Fr 20 ms	^{220}Fr 27 s	^{221}Fr	^{222}Fr	^{223}Fr	^{224}Fr	^{225}Fr
^{210}Rn	^{211}Rn	^{212}Rn	^{213}Rn	^{214}Rn	^{215}Rn 2.3 µs	^{216}Rn 45 µs	^{217}Rn 0.54 ms	^{218}Rn 35 ms	^{219}Rn	^{220}Rn	^{221}Rn	^{222}Rn	^{223}Rn	^{224}Rn
^{209}At	^{210}At	^{211}At	^{212}At	^{213}At	^{214}At	^{215}At 0.1 ms	^{216}At 300 µs	^{217}At 32 ms	^{218}At 1.6 s	^{219}At	^{220}At	^{221}At	^{222}At	^{223}At
^{208}Po	^{209}Po	^{210}Po	^{211}Po	^{212}Po	^{213}Po	^{214}Po	^{215}Po 1.7 ms	^{216}Po 150 ms	^{217}Po 1.5 s	^{218}Po 3.1 m	^{219}Po α, 10 m	^{220}Po α, min		
^{207}Bi	^{208}Bi	^{209}Bi	^{210}Bi	^{211}Bi	^{212}Bi 7,22,65 m	^{213}Bi 45 m	^{214}Bi 19.9 m	^{215}Bi 7.7 m	^{216}Bi 2.2 m	^{217}Bi 1.6 m	^{218}Bi 33 s	^{219}Bi ~10 s	^{220}Bi ~10 s	
^{206}Pb	^{207}Pb	^{208}Pb	^{209}Pb	^{210}Pb	^{211}Pb	^{212}Pb	^{213}Pb	^{214}Pb	^{215}Pb					
^{205}Tl	^{206}Tl	^{207}Tl	^{208}Tl	^{209}Tl	^{210}Tl	^{211}Tl	^{212}Tl							

The Team



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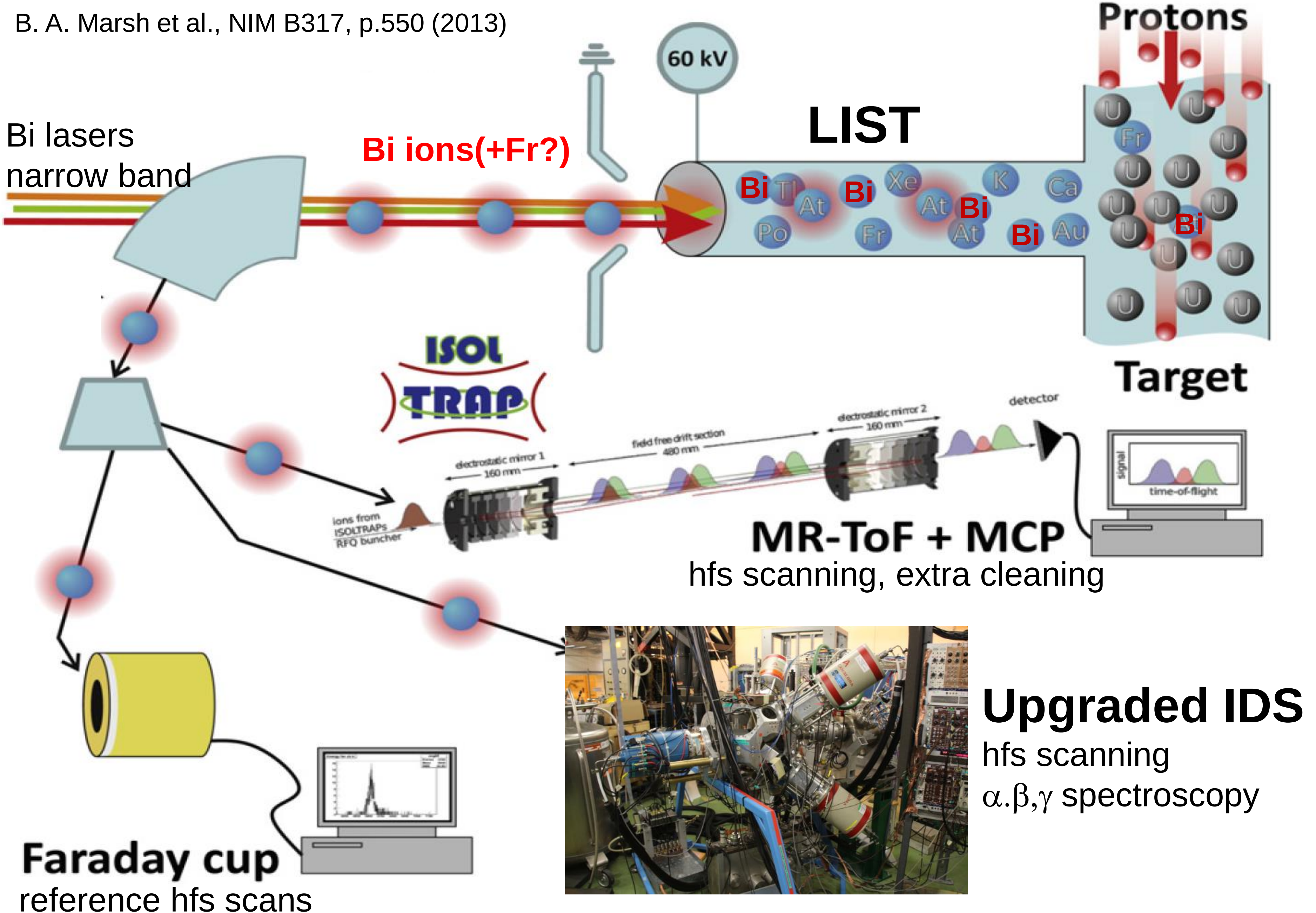
The CRIS team will provide and set-up the “injection-seeded” laser to obtain the “narrow-band” mode.

The Method: In-source laser spectroscopy+IDS+MR-ToF

B. A. Marsh et al., NIM B317, p.550 (2013)



Bi lasers
narrow band

Bi ions(+Fr?)

LIST

Target

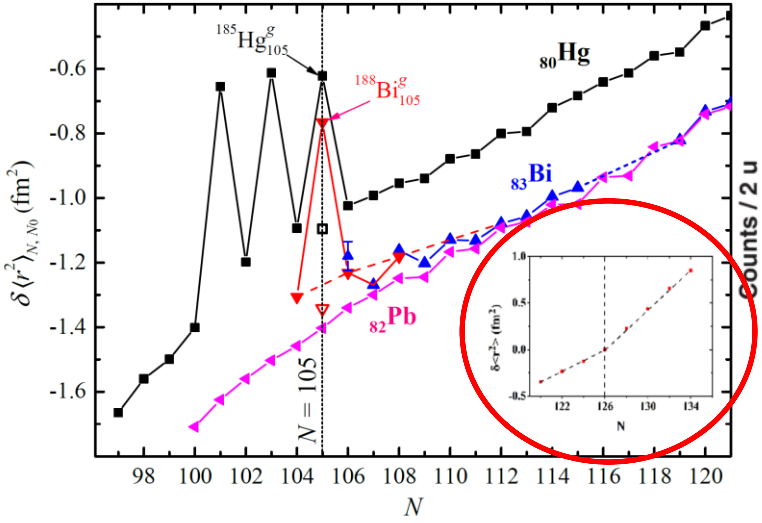
MR-ToF + MCP
hfs scanning, extra cleaning

Upgraded IDS
hfs scanning
α.β,γ spectroscopy

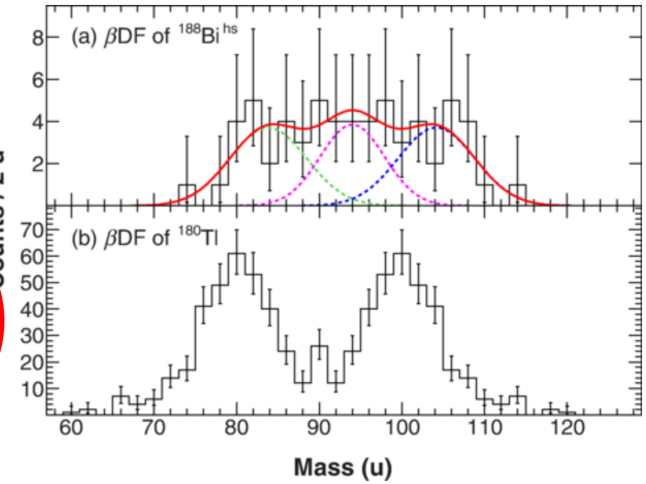
Faraday cup
reference hfs scans

Selected latest results on Bi isotopes (IS608+IS650)

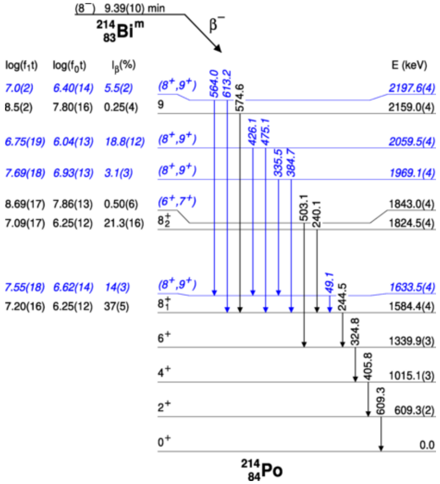
IS608 A.E. Barzakh et al., Shape staggering in gs of $^{187-189}$Bi
Phys. Rev. Lett. 127, 192501 (2021)



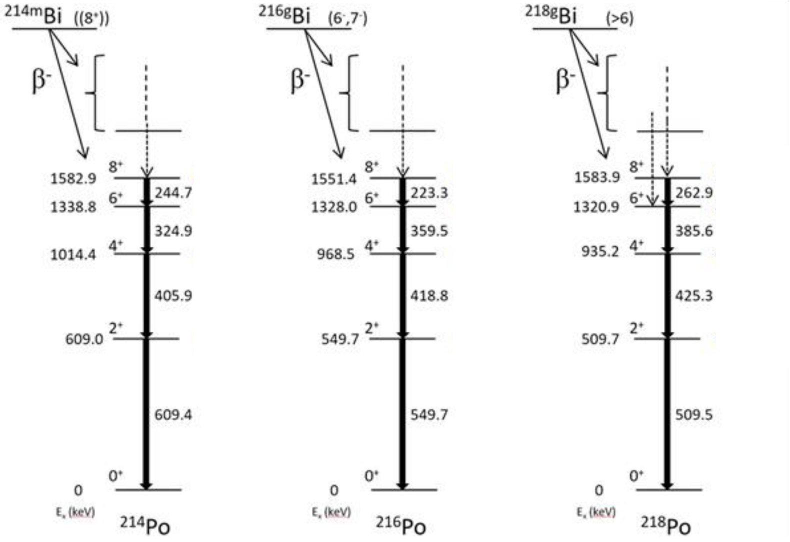
IS608 B. Andel et al., ^{188}Bi beta-delayed fission
Phys. Rev. C 102, 014319 (2020)



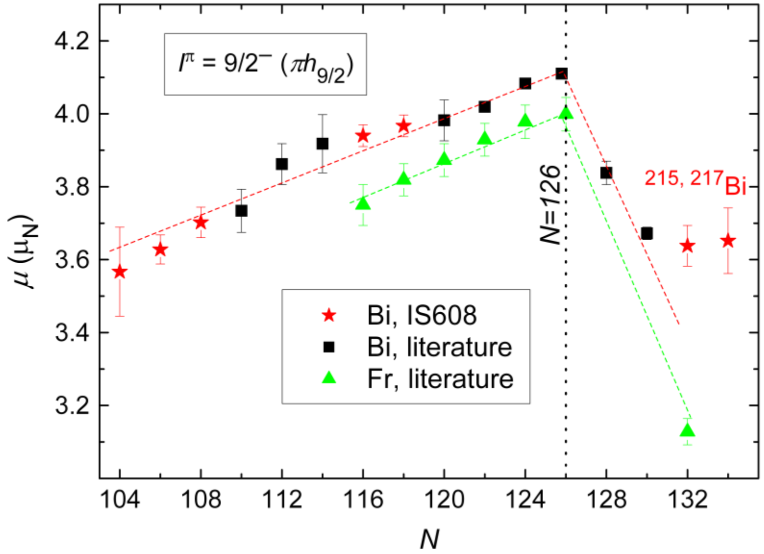
IS650 B. Andel et al., New isomer in ^{214}Bi
Phys. Rev. C 104, 054301 (2021)



IS650, fast timing, 8⁺ isomers; R.Lica in preparation
Also provided yield measurements up to ^{218}Bi



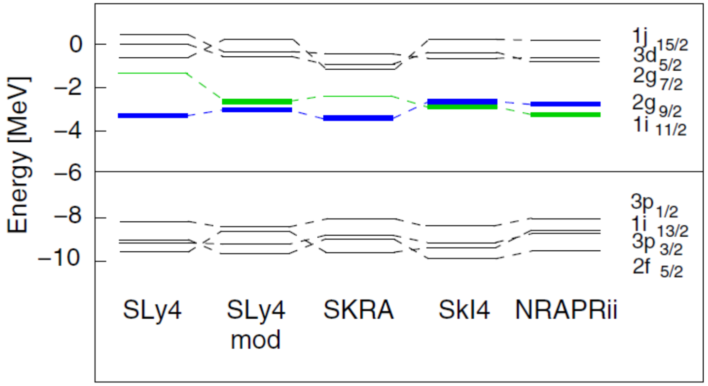
IS608, Anomaly of the gs 9/2⁻ magnetic moments in ^{215,217}Bi
unpublished, needs confirmation – requested now

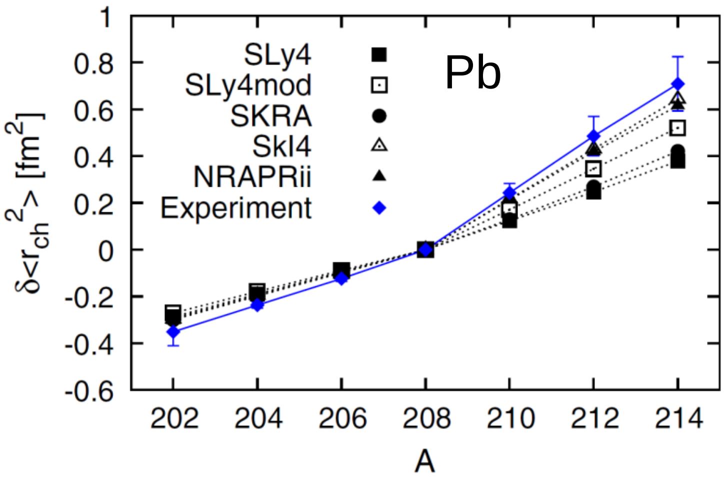


Goal 1: High-spin isomers ^{212m1,m2,213m}Bi and the N=126 kink problem

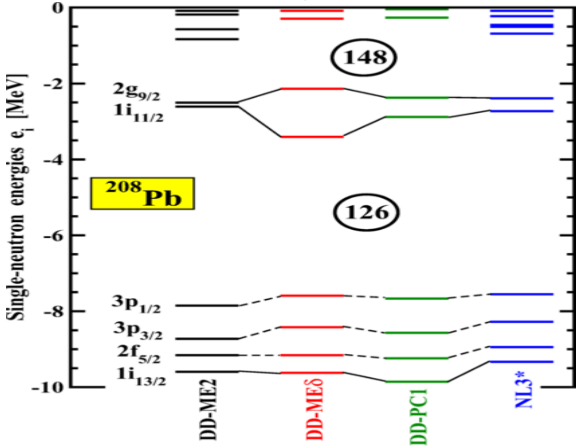
Goal 1. Properties of the high-spin isomers ^{212m1,m2,213m}Bi and their link to the Bi gs charge radii kink at N=126: is the position and occupation of the i11/2 neutron orbital relative to g9/2 a real culprit for the N=126 kink?

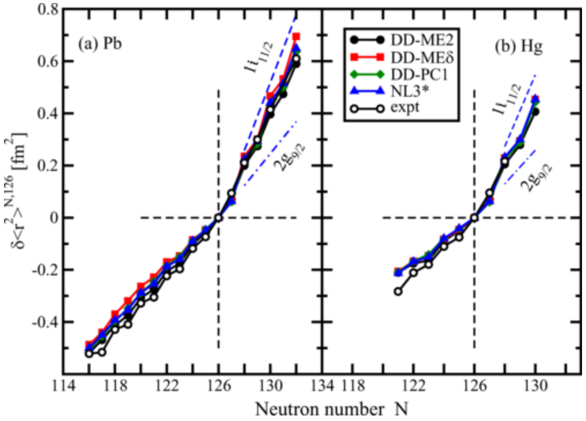
Skyrme, P.M. Goddard et al,PRL110 (2013)

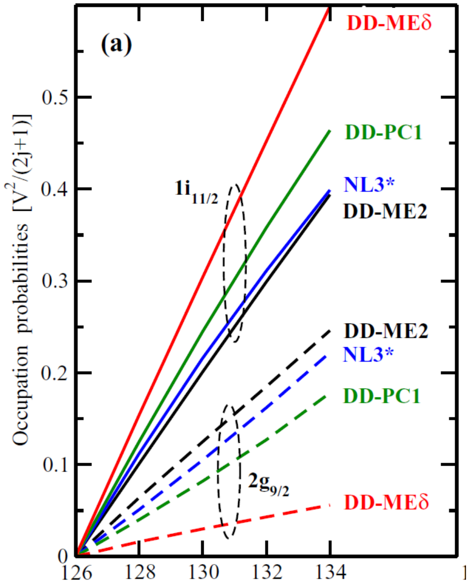




Relativistic, T. Day Goodacre et al,PRL126(2021)&PRC104(2021)







It seems the models in which **the i11/2 neutron orbital is below g9/2** (or very close to it) reproduce the kink better**, due to enhanced population of the i11/2 orbital. In particular, this is a common property of relativistic approaches.**

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Goal 1. Properties of the high-spin isomers ^{212m1,m2,213m}Bi and their link to the kink in Bi gs charge radii at N=126: is the position and occupation of the i11/2 neutron orbital a real culprit for the N=126 kink?

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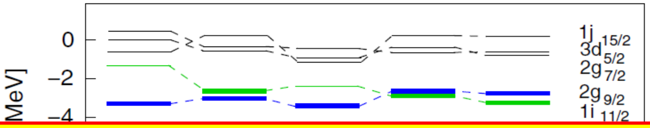
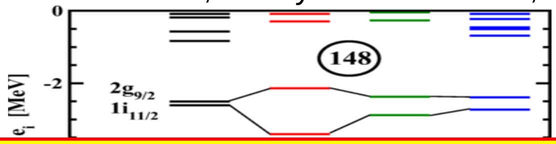
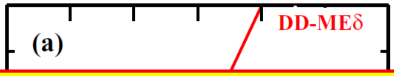


Relativistic, T. Day Goodacre et al, PRC104,054322(2021)





This effect can be probed by charge radii of high-spin isomers in ^{212m2,213m}Bi, whose configuration does include an i11/2 neutron:

^{212m2}Bi [πh9/2×((νg9/2)^{2}×**νi11/2**)]18^{-},

^{213m}Bi [πh9/2× (νg9/2×**νi11/2**)]25/2^{-},

relative to their gs's or ^{212m1}Bi [πh9/2×νg9/2)]8^{-},9^{-}, which have less/no i11/2 neutrons.

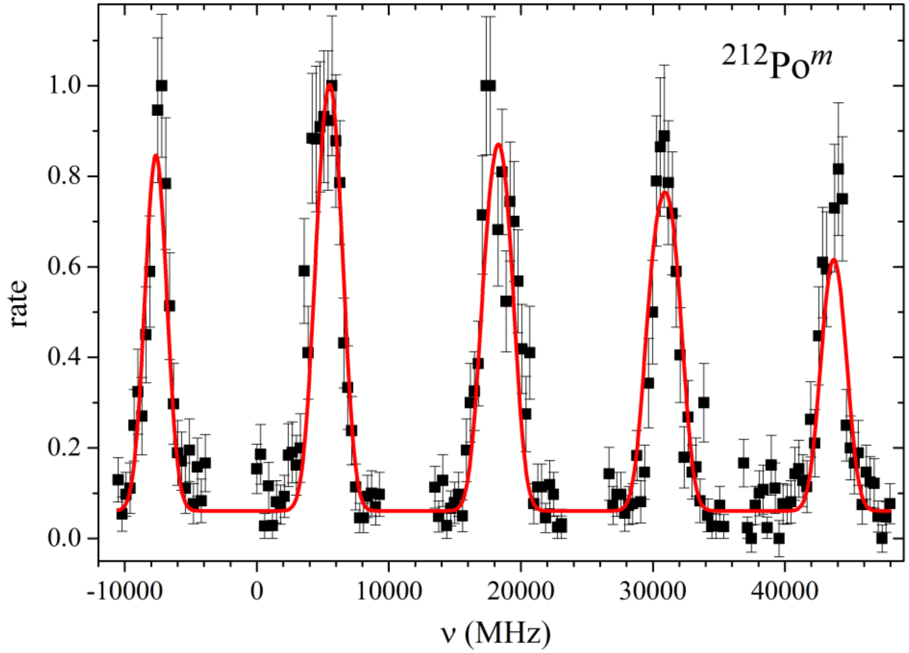
Task 1: We will perform **hfs scanning for ^{212m2,213m}Bi** with LIST in narrowband mode (procedure confirmed for Po/Ac's in our 2022 campaigns. If yields allows, can also try PI-LIST). Some scanning can be done with MR-ToF (for longest-lived cases, if IDS is not enough). Deduced magnetic moments will help to confirm/establish the configurations.

Task 2: Decay properties of some of these isomers are poorly known, studied mostly some 40-50 years ago. We can now do it much better with the versatile IDS system, e.g. to search for the IT decay from 18^{-} to 8/9^{-} (or even to the gs) in ^{212m2}Bi, and/or to measure for the 1st time the half-life of ^{213m}Bi.

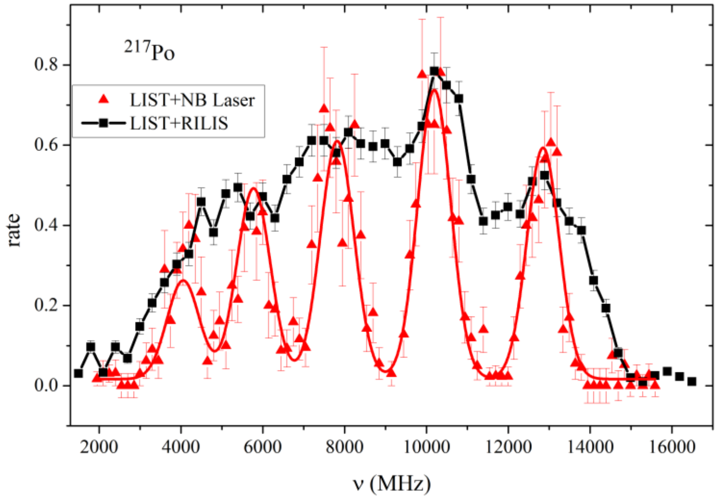
Examples of narrow-band scanning for ^{212m,217}Po (April 2022) and simulations for ^{212g,m1,m2}Bi

CRIS “injection-seeded” narrowband laser (April 2022)

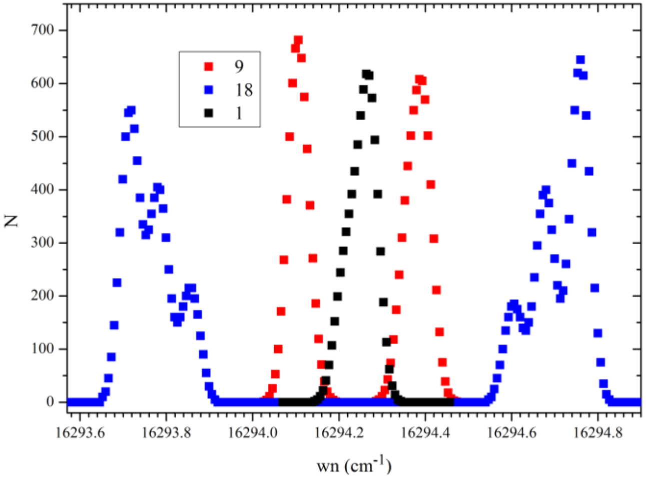
Long scans, ~200 laser steps are needed



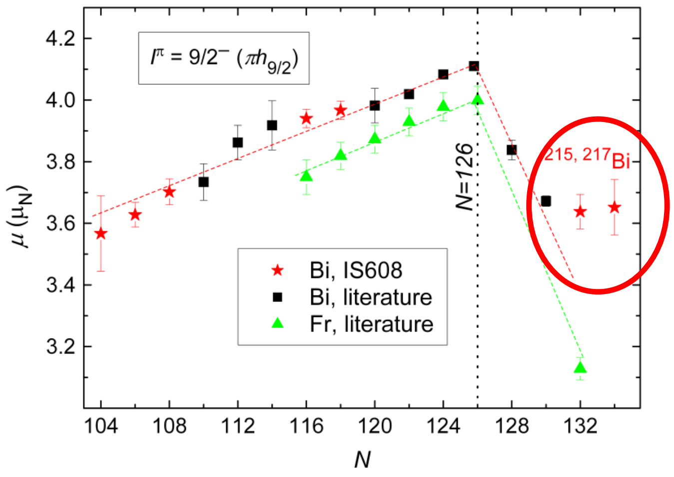
^{217}Po, usual LIST vs NB LIST

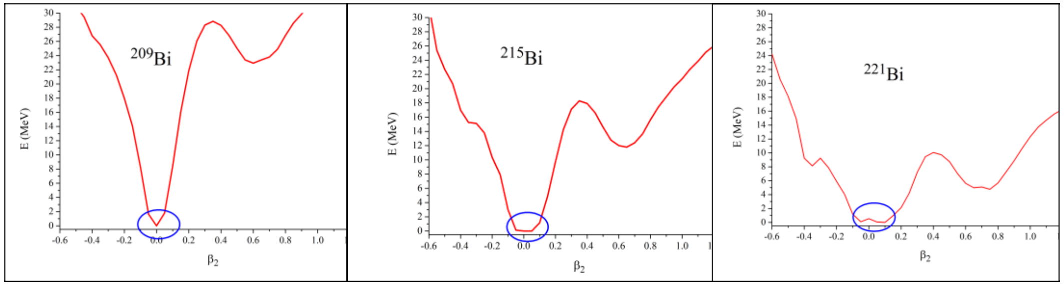


NB Simulations for ^{212g,m1,m2}Bi (A. Barzakh)

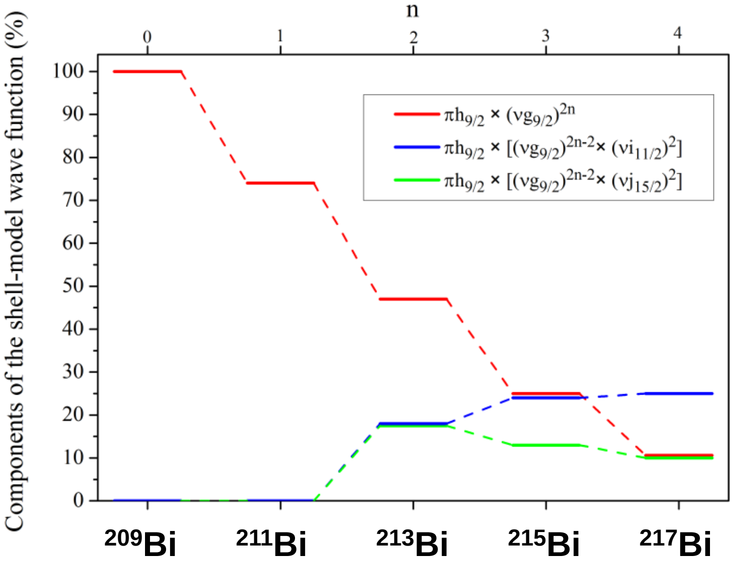


Goal 2: Anomalous 9/2⁻ gs magnetic moment systematics in ^{215,217}Bi: evidence for deformation/configuration mixing?

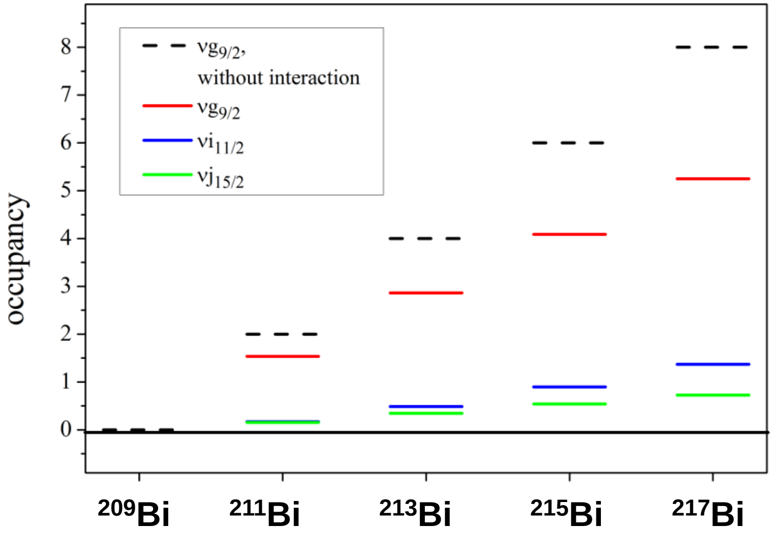




PES for ^{209,215,221}Bi calculated in HFB approach with Gogny forces D1S. A clear change of the PES minimum can be noticed by moving to heavier isotopes – deformation effects due to configuration mixing in the gs, via occupation of the high-j neutron orbitals?



The shell-model wave function components for the 9/2⁻ gs of the even-N Bi isotopes. Only components with the weight larger than 10% are shown (H. Naïdja)



The neutron shells occupancies for the 9/2⁻ gs of the even-N Bi isotopes. Black dashed lines correspond to artificial situation with sequential g9/2 shell filling, while red/blue/green lines correspond to the inclusion of the effective interaction. (H. Naïdja)

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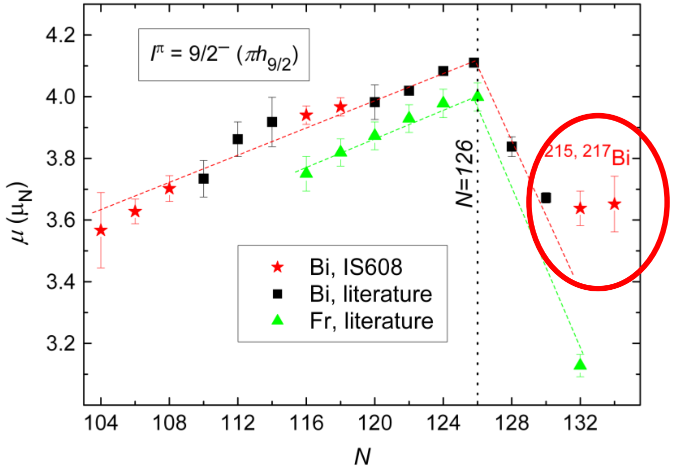
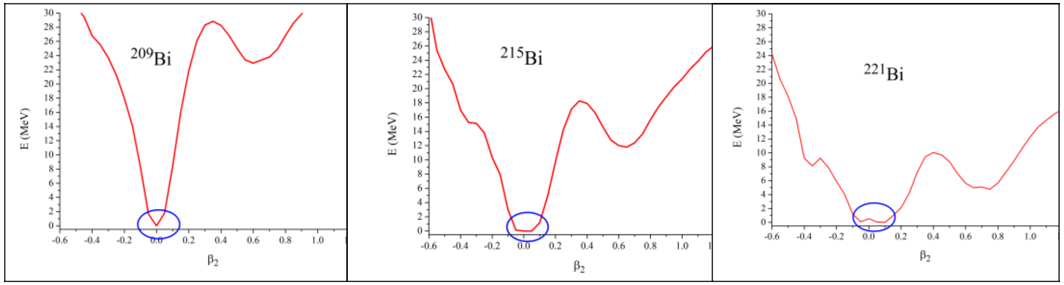
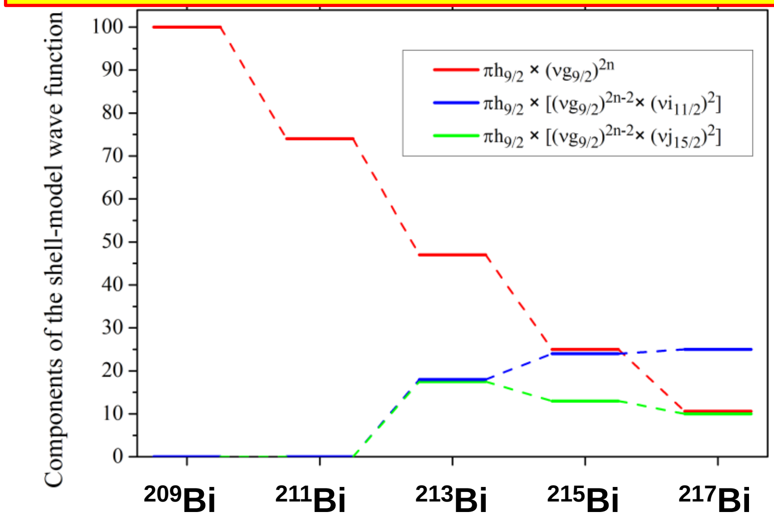


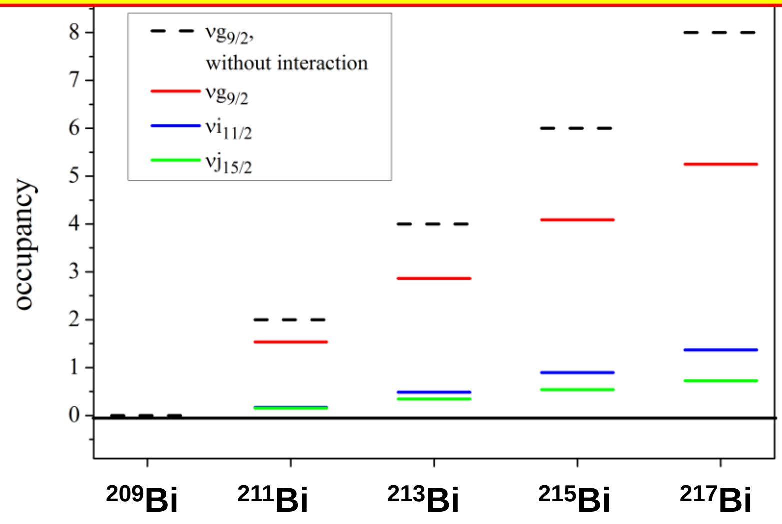


PES for ^{209,215,221}Bi calculated in HFB approach with Gogny forces D1S. A clear change of the PES minimum can be noticed by moving to heavier isotopes – deformation effects due to configuration mixing in the gs, via occupation of the high-j neutron orbitals?

Task 3: To be able to publish these data, we need to confirm the observed deviation and improve uncertainties.

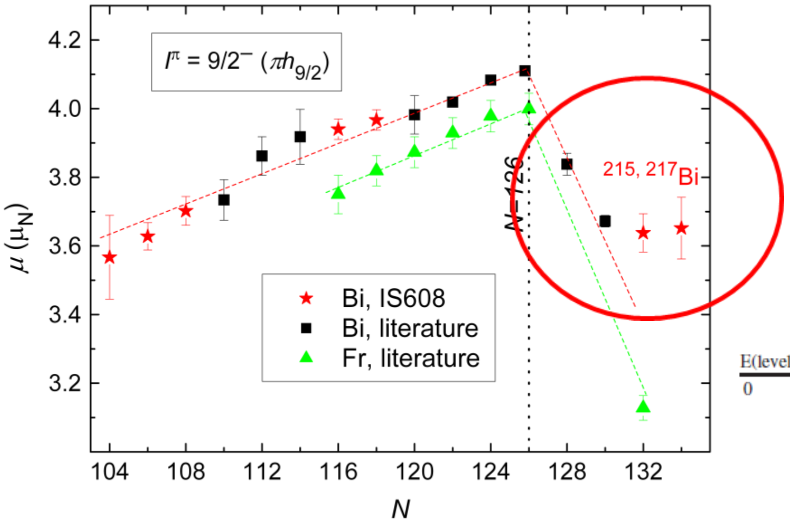


The shell-model wave function components for the 9/2⁻ gs of the even-N Bi isotopes. Only components with the weight larger than 10% are shown (H. Naïdja)

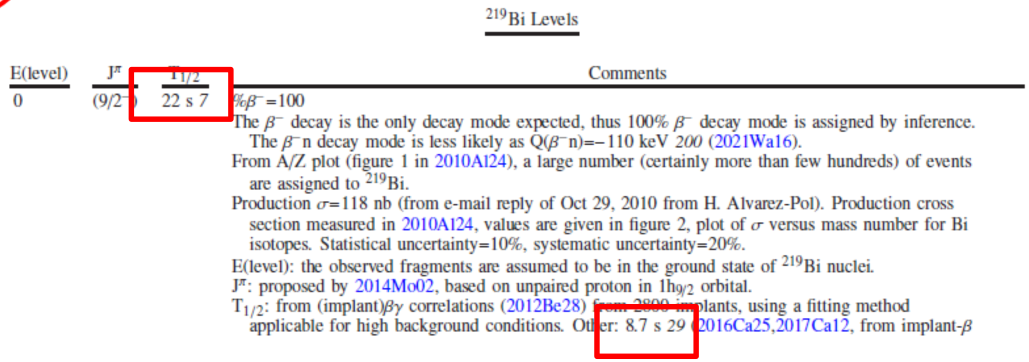


The neutron shells occupancies for the 9/2⁻ gs of the even-N Bi isotopes. Black dashed lines correspond to artificial situation with sequential g9/2 shell filling, while red/blue/green lines correspond to the inclusion of the effective interaction. (H. Naïdja)

Goal 3: First hfs measurements and "first" nuclear spectroscopic data for ^{219,220}Bi (only half-lives are known)



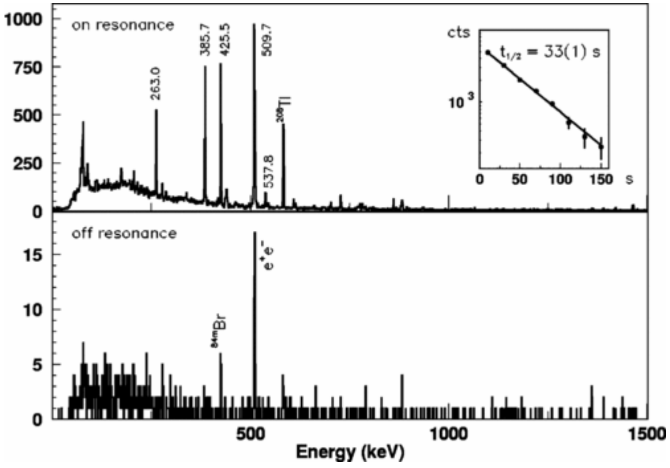
Task 4: Extension of μ-systematics to ^{219}Bi
Task 5: Nuclear spectroscopy data for ^{219,220}Bi



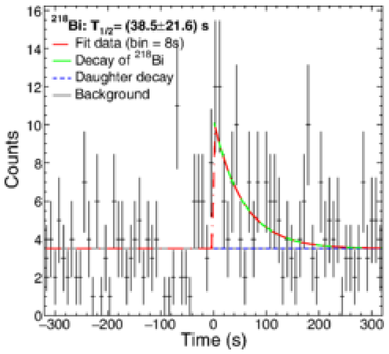
^{219}Bi Levels

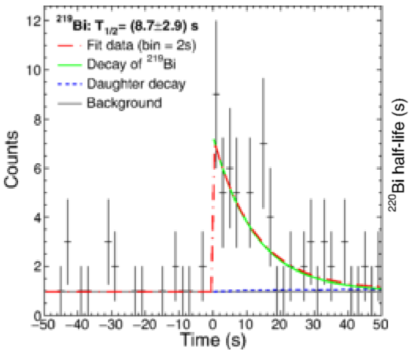
E(level)	J^{π}	$T_{1/2}$	Comments
0	(9/2−)	22 s 7	%β^-=100 The β^- decay is the only decay mode expected, thus 100% β^- decay mode is assigned by inference. The β^-n decay mode is less likely as Q(β^-n)=−110 keV *200* (2021Wa16). From A/Z plot (figure 1 in 2010Al24), a large number (certainly more than few hundreds) of events are assigned to ^{219}Bi. Production σ=118 nb (from e-mail reply of Oct 29, 2010 from H. Alvarez-Pol). Production cross section measured in 2010Al24, values are given in figure 2, plot of σ versus mass number for Bi isotopes. Statistical uncertainty=10%, systematic uncertainty=20%. E(level): the observed fragments are assumed to be in the ground state of ^{219}Bi nuclei. J^{π}: proposed by 2014Mo02, based on unpaired proton in 1h$_{9/2}$ orbital. $T_{1/2}$: from (implant)$\beta\gamma$ correlations (2012Be28) from 2800 implants, using a fitting method applicable for high background conditions. Other: 8.7 s *29* (2016Ca25,2017Ca12, from implant-β

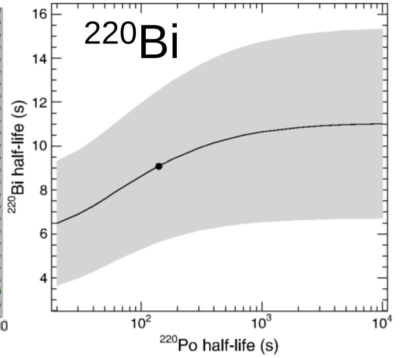
H. De Witte et al., PRC69, (2004)
^{218}Bi@ISOLDE, 45 atoms/μC
(~200 atoms/μC in IS650)



^{218,219,220}Bi@FRS-GSI, R. Caballero-Folch et al., PRC95 (2017),
~200-300 implanted nuclei in total for each







Beam request

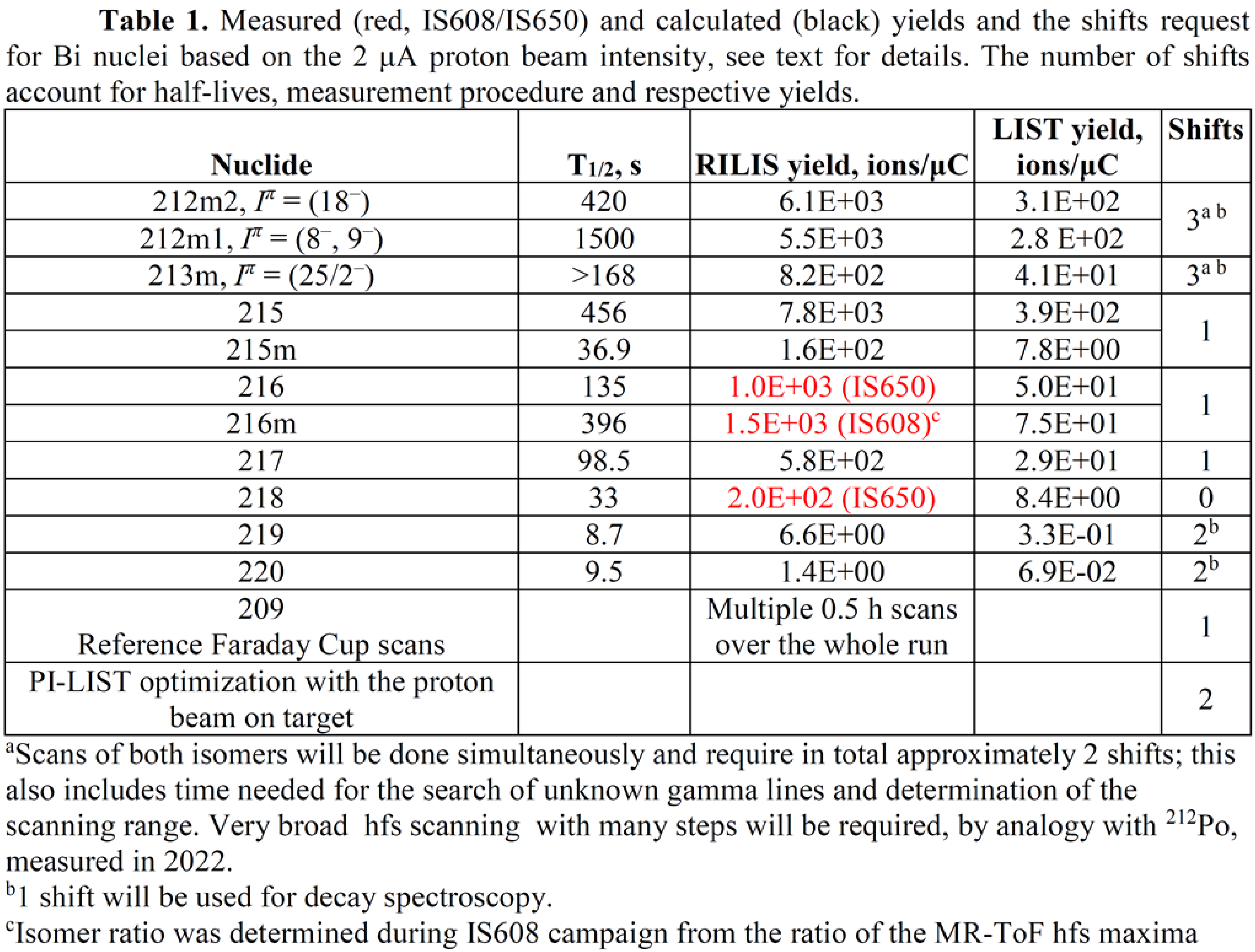


Table 1. Measured (red, IS608/IS650) and calculated (black) yields and the shifts request for Bi nuclei based on the 2 μA proton beam intensity, see text for details. The number of shifts account for half-lives, measurement procedure and respective yields.

Nuclide	$T_{1/2}$, s	RILIS yield, ions/μC	LIST yield, ions/μC	Shifts
212m2, $I^{\pi} = (18^{-})$	420	6.1E+03	3.1E+02	$3^{a\ b}$
212m1, $I^{\pi} = (8^{-}, 9^{-})$	1500	5.5E+03	2.8 E+02	
213m, $I^{\pi} = (25/2^{-})$	>168	8.2E+02	4.1E+01	$3^{a\ b}$
215	456	7.8E+03	3.9E+02	1
215m	36.9	1.6E+02	7.8E+00	
216	135	1.0E+03 (IS650)	5.0E+01	1
216m	396	1.5E+03 (IS608)[c]	7.5E+01	
217	98.5	5.8E+02	2.9E+01	1
218	33	2.0E+02 (IS650)	8.4E+00	0
219	8.7	6.6E+00	3.3E-01	2^{b}
220	9.5	1.4E+00	6.9E-02	2^{b}
209 Reference Faraday Cup scans		Multiple 0.5 h scans over the whole run		1
PI-LIST optimization with the proton beam on target				2

[a] Scans of both isomers will be done simultaneously and require in total approximately 2 shifts; this also includes time needed for the search of unknown gamma lines and determination of the scanning range. Very broad hfs scanning with many steps will be required, by analogy with ^{212}Po, measured in 2022.

[b] 1 shift will be used for decay spectroscopy.

[c] Isomer ratio was determined during IS608 campaign from the ratio of the MR-ToF hfs maxima

In total, 16 shifts requested for hfs/IS, nuclear spectroscopy and reference measurements

TAC comments-1

- The requested yields are based on a previous RILIS run. A factor of 20 is applied for LIST losses which, for some cases, is on the optimistic side.
  - Agree, but for most of cases, e.g. at least for $^{213-218}$Bi, we are still at a good level, even with a larger "suppression factor" of, say, 50: e.g. 2 cps for ^{218}Bi instead of 8 cps, see previous slide. Our measurement limit is ~0.01 cps (depends on the decay mode/background)

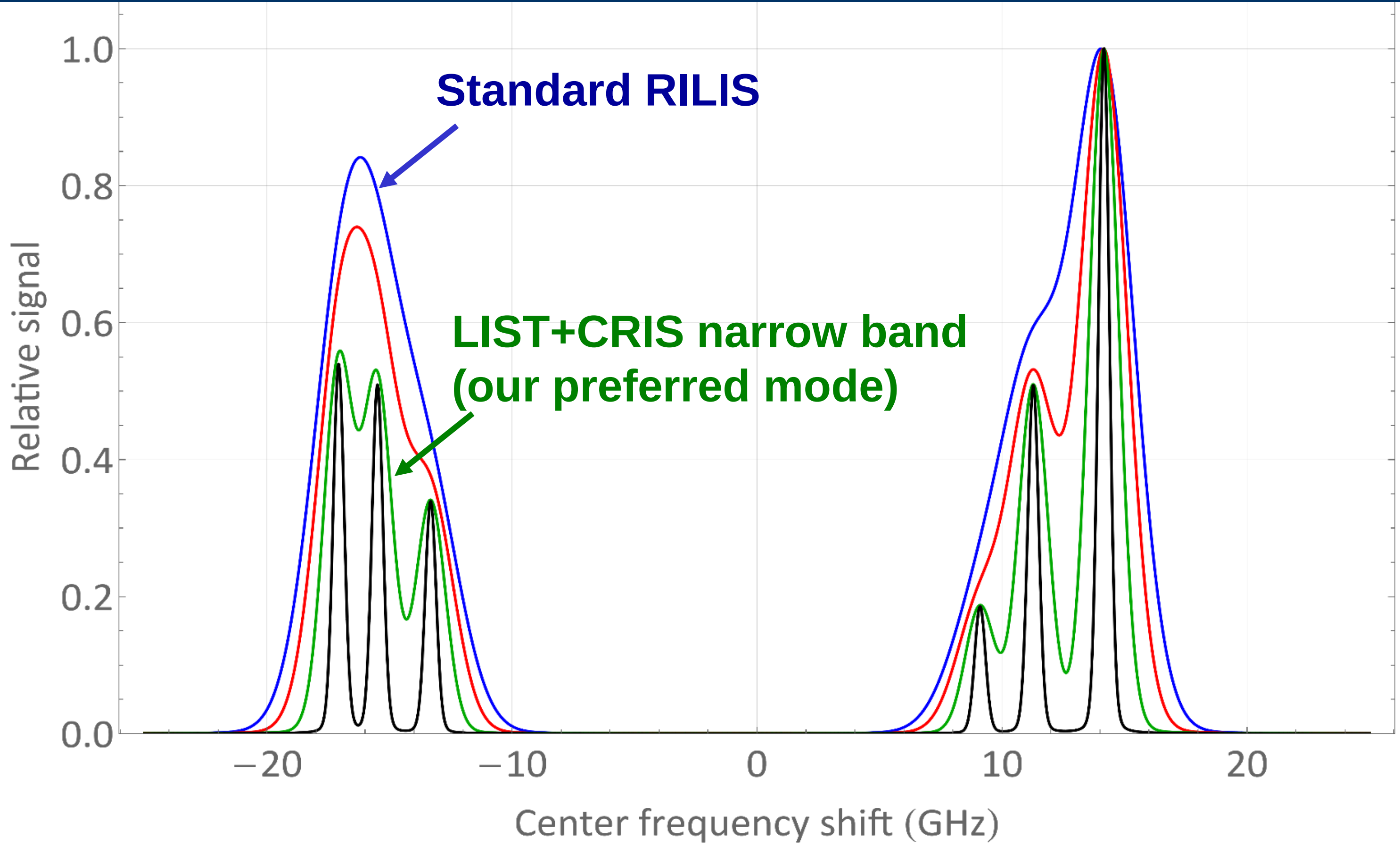
- It should be noted that running in PI-LIST will have much higher losses, up to a factor of 1000, but the sensitivity of IDS should still allow for successful measurements.
  - We might not need to use PI-LIST at all, especially for the most difficult cases, and will just use a 'narrow-band' laser from CRIS, this will avoid extra losses, still keeping a suitable hfs resolution (was proven in Po/Ac LIST runs in 2022). See also the simulated spectrum for ^{209}Bi

- The suppression of Fr can vary along the isotopic chain, fluctuations are to be expected.
  - Noted, and we have large experience with those Fr's, should be ok with IDS. Also, in some cases we can use MR-ToF scanning

- The yields of $^{213-215}$Bi seem credible. For ^{216}Bi, there are no data in the ABRABLA database: where did this figure come from?
  - Yields for $^{214-218}$Bi were measured in IS650 (previous slide); also earlier in our ISOLDE experiments some 15 years ago, during our first measurements up to ^{218}Bi (nuclear spectroscopy with RILIS), thus we are fully confident for reaching up to ^{218,219}Bi

Do we really need PI-LIST mode?

Simulations for ^{209}Bi (R. Heinke)



- **Blue:** Standard in-source spectroscopy + dual etalon laser (~2.9GHz)
- **Red:** LIST collinear mode + dual etalon laser (~2.2GHz) – The better resolution comes from the fact that the LIST only probes atoms flying towards the laser into the LIST. There will be a shift against the other modes.
- **Green: LIST collinear mode + CRIS narrowband laser (~1.4GHz) – our preferred mode of operation here**
- **Black:** PI-LIST mode + CRIS narrowband laser (~0.5GHz)

Conclusion: no significant improvement with PI-LIST, thus we might not use it at all (TAC asked on PI-LIST intensity reduction)

TAC comments-1

- The requested yields are based on a previous RILIS run. A factor of 20 is applied for LIST losses which, for some cases, is on the optimistic side.
  - Agree, but for most of cases, e.g. at least for $^{213\text{-}218}$Bi, we are still at a good level, even with a larger “suppression factor” of, say, 50: e.g. 2 cps for ^{218}Bi instead of 8 cps, see previous slide. Our measurement limit is ~0.01 cps (depends on the decay mode/background)

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TAC comments- 2

- It should be noted that the **yields of $^{219\text{-}220}$Bi could be very low** and can’t be guaranteed. In the case of low to no yields on these isotopes, are the physics goals of the experiment still reachable?
- \- Fully agree on the comment on ‘very low’ yields for ^{219,220}Bi, but our previous IDS studies showed that we can reliably measure down to 0.01 cps, which is still a factor of 5 below the rate we expect for ^{219,220}Bi (see previous slide).

  -While we are pretty confident to reach ^{219}Bi, ^{220}Bi might indeed be not possible, and might have to be abandoned from our program if nothing/too few is seen. However, while not endangering the core objectives of this proposal, the ^{220}Bi measurement represents a high-risk, high-gain component that should be investigated.

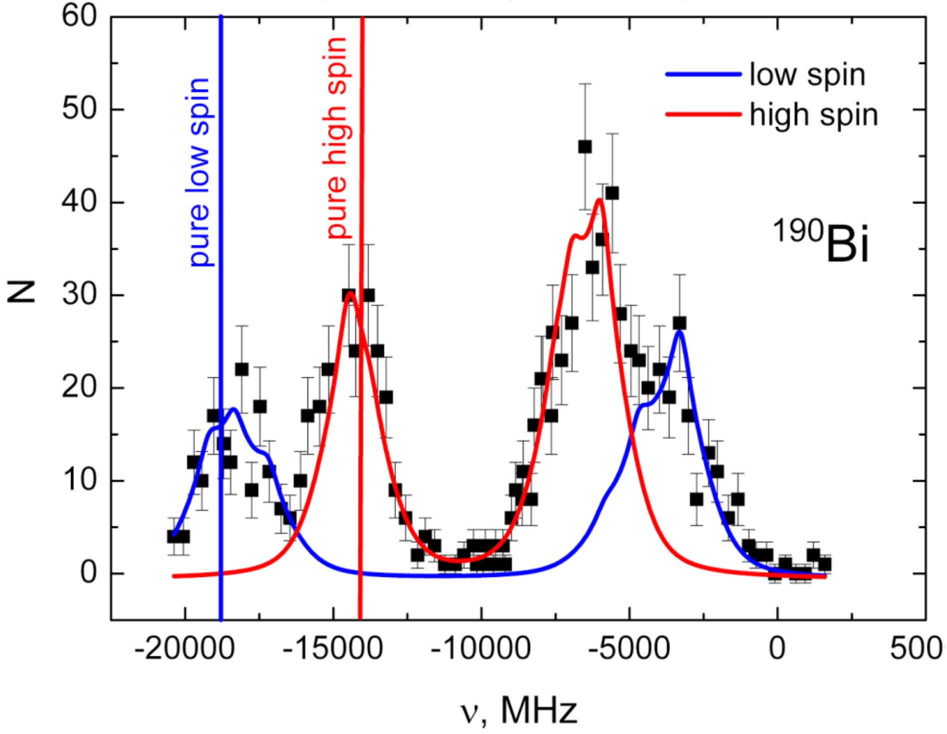
- RILIS with LIST requires considerable input from the RILIS team, and additional setting up time, but feasible.

  -Yes, that’s why we requested 2 extra shifts for the LIST setup, also for the setup of narrow-band CRIS laser. If ^{220}Bi is not possible, we could spend more time on better LIST tuning/exploration of its modes (and also do more in the PI-LIST mode if find suitable).
  We also requested a week “off-line” (before the run) for setting up of this narrow-band laser (it is mentioned on the safety form).

Thank you!

Isomer separation in ^{190m1,m2}Bi (IRIS@PNPI, Gatchina)

Courtesy A.Barzakh (IRIS@PNPI)



Based on expected similarity of configurations in ^{188m1,m2}Bi and in ^{190m1,m2}Bi, isomerically-pure beams of ^{188m1,m2}Bi should be obtained for βDF study

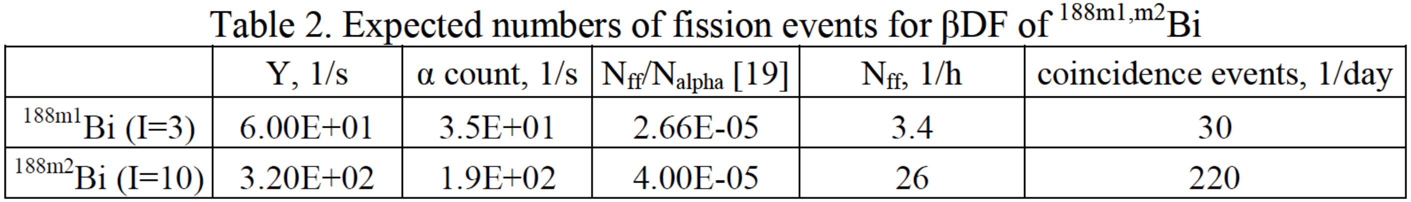


Table 2. Expected numbers of fission events for βDF of ^{188m1,m2}Bi

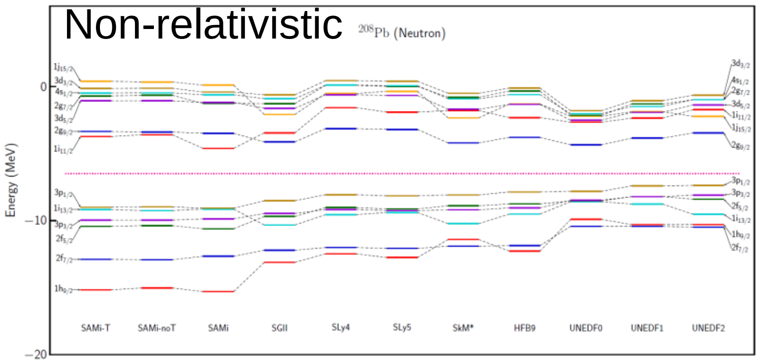
	Y, 1/s	α count, 1/s	N_{ff}/N_{alpha} [19]	N_{ff}, 1/h	coincidence events, 1/day
^{188m1}Bi (I=3)	6.00E+01	3.5E+01	2.66E-05	3.4	30
^{188m2}Bi (I=10)	3.20E+02	1.9E+02	4.00E-05	26	220

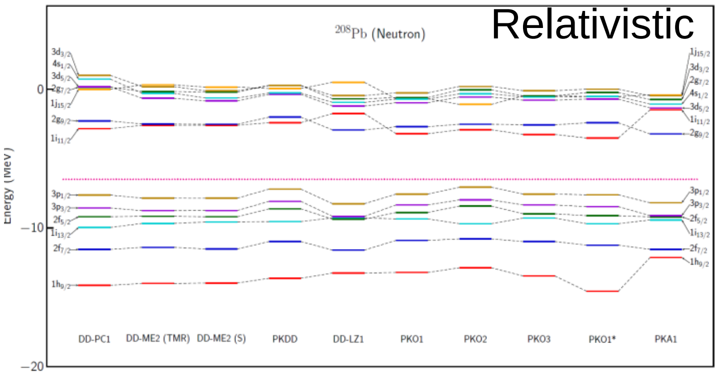
16 Shifts Requested for βDF measurements of ^{188}Bi at ISOLDE
Measurements to be performed with the Windmill setup

Physics Motivation and goals of the proposal
Goal 1: The N=126 kink problem

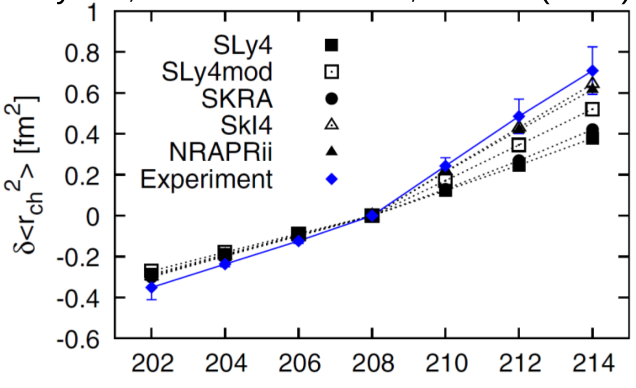
Goal 1. Properties of the high-spin isomers ^{212m1,m2,213m}Bi and their possible link to the kink in Bi ground state charge radii at N=126: is the population of the i11/2 neutron orbital a real culprit for the N=126 kink?

T. Naito et al., RIKEN, arXiv:2209.028572v2

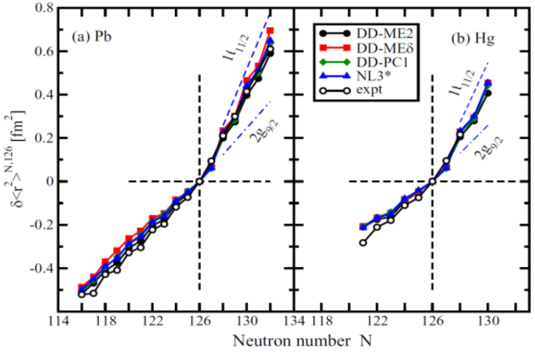

Non-relativistic

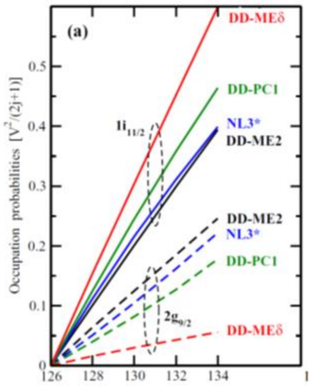

Relativistic

Skyrme, P.M. Goddard et al,PRL110 (2013)



T. Day Goodacre et al, PRC104,054322(2021)





It seems the models in which **the i11/2 neutron orbital is below g9/2** (or very close to it) reproduce the kink better**, due to enhanced population of the former orbital.** If so, this effect can be probed by charge radii of high-spin isomers in ^{212,213}Bi, whose configuration does include an i11/2 neutron: ^{212m2}Bi [πh9/2×((νg9/2)^2×νi11/2)]18–, ^{213m}Bi [πh9/2× (νg9/2×νi11/2)]25/2–, relative to their gs's or ^{212m1}Bi, with less or no i11/2 neutrons (e.g. ^{212m1}Bi [πh9/2×νg9/2)]8–,9–).