CERN-INTC-2023-003 / INTC-P-649
12/01/2023

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

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

A.N. Andreyev[1], A.E. Barzakh[2], B. Andel[3], S. Antalic[3], S. Bara[4], C. Bernerd[4,5], A. Candiello[4], K.Chrysalidis[5], T.E. Cocolios[4], J. Cubiss[1], H. De Witte[4], M. Deseyn[4], R. de Groote[4], D.V. Fedorov[2], V.N. Fedosseev[5], K.T. Flanagan[6], G. Georgiev[7], M. Heines[4], R. Heinke[5], A.A.H. Jaradat[5,6], J.D. Johnson[4], U. Koster[8], R. Lica[9], K. Lynch[6], R. Mancheva[4,5], B.A. Marsh[5], A. McGlone[6], C. Mihai[9], H. Naïdja[10], G. Neyens[4], C.Page[1], S. Rothe[5], M.D. Seliverstov[2], P. Van Duppen[4], W. Wojtaczka[4], Z.Yue[1], D. Balabanski[11], A. Kusoglu[11], G.Rainovski[12], K. Gladnishki[12], D. Kocheva[12], K. Stoychev[7], Y. Hirayama[13], M. Mukai[14], J. Reilly[6], T. Niwase[13], Y. Watanabe[13], J.Wessolek[6], A.Algora[15], J.Jolie[16], A.Blazhev[16], N.Warr[16], Z. Podolyak[17], L.Gaffney[18], A. Korgul[19], A. Illana[20], Y. Litvinov[21], L.Nies[5,22], C. Schweiger[23], D. Lange[23], A. Morales[24]+IDS Collaboration +ISOLTRAP/MR-ToF Collaboration

[1]University of York, U.K., [2]Petersburg Nuclear Physics Institute, Gatchina, Russia, [3]Department of Nuclear Physics and Biophysics, Comenius University in Bratislava, Slovakia, , [4]IKS-KULeuven, Belgium, [5]CERN-ISOLDE, Switzerland, [6]University of Manchester, UK, [7]IJCLab/IN2P3/CNRS, Orsay, France, ILL, [8]Grenoble, France, [9]IFIN-HH, Romania, [10]Université Constantine 1, Algeria, [11]ELI-NP, Bucharest, Romania, [12]Sophia University, Bulgaria, [13]WNSC, IPNS, KEK, Japan, [14]RIKEN, Japan, [15]University of Valencia, Spain, [16]IKP, University of Cologne, Germany, [17]University of Surrey, UK, [18]University of Liverpool, UK, [19]Warsaw University, Poland, [20]Universidad Complutens de Madrid, Madrid, Spain, [21]GSI (Germany), [22]Universität Greifswald, Germany, [23]Max-Planck-Institut für Kernphysik, Heidelberg, Germany, [24]IFIC, CSIC-University of Valencia, Spain

Spokesperson: A.N. Andreyev (York)
Co-spokesperson: T.E Cocolios (KU Leuven)
Local Contact Person: R. Heinke (CERN)

Abstract

In 2016-2018, successful β-delayed fission and in-source laser spectroscopy campaigns (IS608) for many isotopes in the range of $^{187\text{-}218}$Bi were performed by the Windmill/IDS/MR-ToF collaboration, along with a fast-timing β–γ decay study of ^{214,216,218}Bi (2018, IS650).

We propose to complete these studies by measuring changes in the mean-square charge radii ($\delta\langle r^2\rangle$) and electromagnetic moments of the high-spin isomers in ^{212,213}Bi and the heavier isotopes $^{215,216.217.219,220}$Bi. These results will help to develop the microscopic understanding of the kink in the charge radii at N=126, testing and validating large-scale shell model calculations via magnetic and quadrupole measurements and probing the presence of octupole deformation in the neutron-rich bismuth isotopes. The studies of ^{212,213}Bi isotopes were accepted by INTC within the initial IS608 program, but were inaccessible in our previous experiments due to overwhelming contamination from the Fr and Ra isobars. We will overcome this obstacle by using the (PI-)LIST, which efficiently suppresses them, as was shown in our successful Po and Ac runs in spring 2022. The enhanced resolution provided by PI-LIST (or dedicated narrow-band laser) will allow the first determination of quadrupole moments for some of these isotopes. Further increase in sensitivity will be achieved by using enhanced detection capabilities provided by the upgraded ISOLDE Decay Station (IDS).

Requested shifts: **16 in one run with the LIST (PI-LIST)**

I. Introduction: Selected results of the IS608/IS650 campaigns

In the 2016-2018 IS608 campaign, the Bi electromagnetic moments and the changes of the mean squared charge radii, $\delta\langle r^2\rangle$, were obtained via the isotope shift (IS) and hyperfine structure (hfs) investigation for $^{187\text{-}191,194\text{-}202,214\text{-}218}$Bi (in total, 27 nuclei). Dedicated fast timing studies of excited states in ^{214,216,218}Po were performed following the β decay of ^{214,216,218}Bi precursors in IS650 (July 2018). The list of selected results, either published (#1-3 below) or in preparation for publications (#4-7 below) is as follows.

1. A striking charge radius staggering was observed for ^{188}Bi^{g} relative to ^{187,189}Bi^{g}, at the same neutron number, N = 105, where the Hg shape staggering starts in ^{185}Hg^{g} (Fig.1) and of similar magnitude. It is only the second example of such unusual staggering throughout the nuclide chart. The results were published in the PRL paper [Ba21].
2. β-delayed fission of the laser-separated isomeric and ground states (gs) of ^{188}Bi was performed and the results compared state-of-the-art fission models [An20].
3. A detailed β–γ spectroscopy (IS650) of the new high-spin isomer with $I^{\pi} = (8^{-})$ in ^{214}Bi was investigated [An21], and compared to large scale shell-model calculations.
4. First fast-timing measurements were performed for the 8^{+} sub-microsecond isomers and a range of excited states in ^{214,216,218}Po populated by β decays of the ^{214,216,218}Bi precursors (IS650).
5. Kink in the gs charge radii at N = 126 was established for the Bi chain (see inset in Fig. 1).
6. The presumed linear systematic trend for magnetic moments of the even-N, odd-Z $I^{\pi} = 9/2^{-}$ nuclear ground states in ^{209,211,213}Bi is violated in ^{215,217}Bi (N=132,134), see Fig.2. The confirmation of these results and probing this trend for ^{219}Bi is one of the goals of this proposal.
7. A hint on "inverse" odd-even staggering (OES) was observed in ^{215,216,217}Bi, whereby the radius of the odd-N ^{216}Bi is larger than the mean value of the radii of its two even-N neighbors. This is opposite to the "normal" OES, commonly known in the isotopic chains, and it is usually linked to the development of octupole collectivity, as e.g. in Fr's [Fr OES].

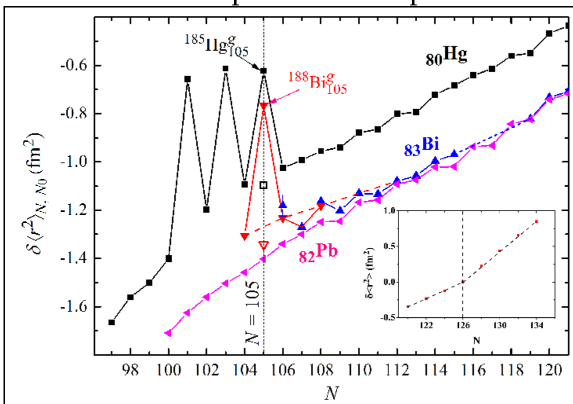

Fig. 1. Comparison of $\delta\langle r^2\rangle$ values for Bi, Pb and Hg isotopes [Ba21]. N_0 denotes the neutron number for the reference isotope within each chain. In the inset the kink in charge radii at N = 126 for Bi isotopes is shown, established from our IS608 data.

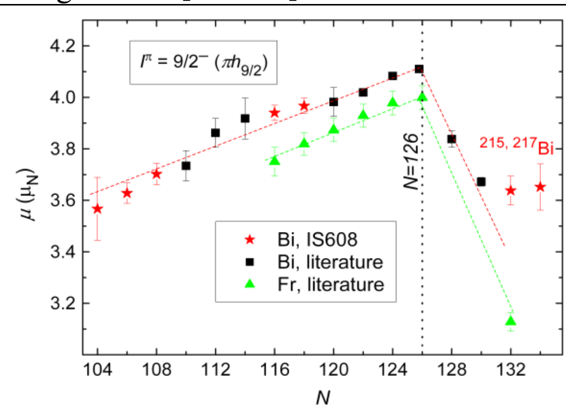

Fig. 2. Magnetic moments of $I^{\pi} = 9/2^{-}$ gs for Fr and Bi even-N isotopes. Points are connected by lines to guide the eyes. While there is a linear N dependence for the magnetic moments in ^{209,211,213}Bi, our preliminary data from IS608 for ^{215,217}Bi strongly deviate from this trend.

II. Motivation for the new proposal

This section outlines the physics motivation and goals for our proposal to study neutron-rich Bi isotopes. We note that some of the ideas discussed below were already presented in our IS608 Addendum in 2018 [http://cds.cern.ch/record/2241202/files/INTC-P-443-ADD-1.pdf?version=1] and the beam time was granted (e.g. for ^{212,213}Bi), but the respective studies could not yet be performed due to the pending LIST developments. Following the successful Po/Ac LIST (PI-LIST) commissioning in several experiments in 2022, we are confident that these studies are now feasible.

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.

High-spin isomers ^{212}Bi ^{m1} [I^{π} = (8^{-},9^{-})], ^{212}Bi ^{m2} [I^{π} = (18^{-})], and ^{213}Bi^{m} [I^{π} = ($25/2^{-}$)] are known, but most data are scarce or even uncertain in some cases and originate from the studies 40-50 years ago [NNDC]. Furthermore, no information on their electromagnetic moments is available and the tentative spin-parity and configurations assignments come mainly from systematics and comparison with shell-model calculations. With the exception of ^{212m1}Bi, their proposed leading configurations involve the presence of an unpaired neutron in the $\nu i_{11/2}$ shell, which is situated above the $g_{9/2}$ orbital in the spherical shell-model approach [Ch12,Ch13]: ^{212}Bi^{m2} $[\pi h_{9/2}\times((\nu g_{9/2})^2\times\nu i_{11/2})]_{18^-}$, ^{212}Bi^{m1} $[\pi h_{9/2}\times\nu g_{9/2})]_{8^-,9^-}$ and ^{213}Bi^{m} $[\pi h_{9/2}\times (\nu g_{9/2}\times\nu i_{11/2})]_{25/2^-}$.

Crucially, in the majority of the theoretical approaches it is the position (relative to the $\nu g_{9/2}$ orbital) and the occupation of the $\nu i_{11/2}$ shell that determines the kink in the gs charge radii at N=126 [Go13], see also our recent study of the Hg isotopes in [Da21]. Consequently, the difference in the $\nu i_{11/2}$ occupancy should lead to a noticeable change in the $\delta\langle r^2\rangle$ for these isomers in comparison with the ground states, provided the interpretation of Refs. [Go13, Da21] is valid, see also a discussion of Fig. 5 below in the text. Thus, one of the main goals of this proposal is to perform first hfs measurements for these isomers to deduce, amongst other data, isomer shifts.

Furthermore, detailed nuclear spectroscopy data will also be obtained for these isomers. For example, only the lower half-life limit of $T_{1/2}$>168 s and E*=1353(21) keV are known for ^{213}Bi^{m} from the measurements at the ESR-GSI storage ring, see Fig.2 of [Ch08], with no decay data available. Different excitation energy values were reported for ^{212}Bi^{m2}: E* > 1.9 MeV from β–decay studies [NNDC] vs E* = 1.48 MeV in ESR-GSI experiment [Ch13]. According to [Ch13], the difference might stem from the presence of the yet unobserved, strong internal decay, for which a value of I(IT)>75% was evaluated. The IT identification will establish the decay path and a range of excited states between the $I^{\pi,m2}$ = (18^{-}) isomer and the isomeric state with $I^{\pi,m1}$ = (8^{-},9^{-}) at E* =239(30) keV [Ch13], or, possibly, directly to the gs, by-passing the m1 isomer. At present, apart from the m2 isomer (either at >1.9 MeV or at ~1.4 MeV) excited states only up to ~500 keV are known in ^{212}Bi. Thanks to new advanced capabilities provided by the upgraded IDS, whereby all decay modes (α/β/γ,CE and, possibly also fast timing) could be observed, such measurements should be straightforward, as demonstrated in the IS650 study of the laser-separated new high-spin isomer in ^{214}Bi [An21].

As a valuable by-product, we will also determine the isomeric ratios, which is an important input for the developers of the yields' simulation codes, such as FLUKA. At present, typically a 50% isomeric ratio is used in such calculations, which is a crude approximation (see also Sec.IV).

2. *Violation of the 9/2⁻ gs magnetic moment systematics in ^{215,217}Bi.*

As mentioned above, Fig.2 shows the deviation of magnetic moments for ^{215,217}Bi^{g} from an apparently linear trend in ^{209,211,213}Bi^{g}. In 2018 we confirmed this deviation for ^{215}Bi, but we need more precise data for ^{217}Bi in order to make the definite conclusions and publish our findings. Besides, because of the limited spectral resolution of the classical in-source laser spectroscopy technique we were not able to determine quadrupole moments of ^{215,217}Bi in our previous experiments, which hampers the reliable interpretation of the observed effect. Measurement of quadrupole moments with reasonable accuracy as well as the reduction of the magnetic moment uncertainty will be possible by using PI-LIST or even collinear, narrow-band laser LIST in the first excitation step, as was demonstrated in our 2022 Ac/Po campaigns. Scaling the achieved experimental resolutions in these experiments to the atomic transition employed for Bi, we expect linewidths of 500 MHz and 1.5 GHz, respectively [He22], as opposed to the Doppler limit of 2.5 GHz for standard RILIS in-source spectroscopy. It is also important to trace the trend of magnetic moments further away from the N = 126, namely, to measure $\mu(^{219}Bi)$. The (PI-)LIST makes this possible.

To understand the possible reasons for this magnetic moment behavior, Fig. 3 shows three representative potential energy surfaces (PES) calculated in the Hartree-Fock-Bogoliubov approach with Gogny forces [Hi_HFB]. For the sake of space constraints, we only show the PES for $^{209,215,221}Bi$ (similar conclusions can be derived from P. Möller's PES calculated in the macro-microscopic approach [Mö12]). While for the semi-magic ^{209}Bi (N = 126) one can see a narrow spherical minimum, it becomes flatter and shallower for the heavier Bi isotopes. This suggests a clear change of gs's nature in Bi isotopes by moving away from the N=126 shell.

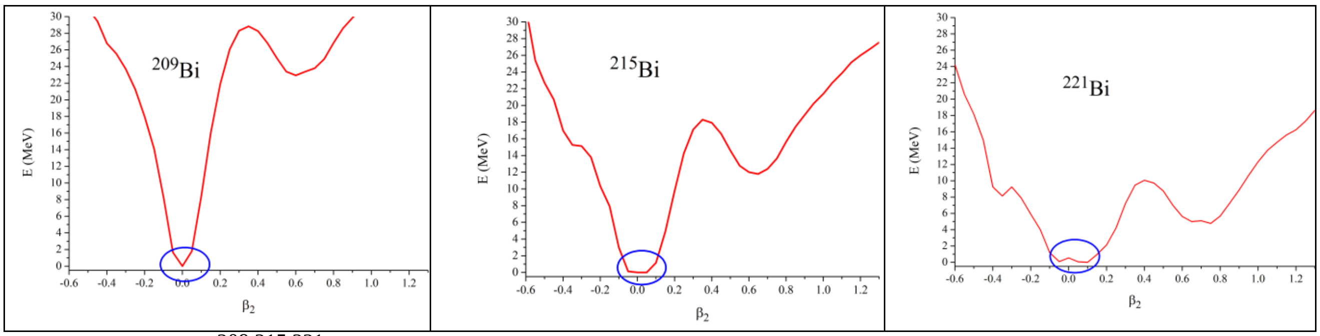

Fig 3. PES for $^{209,215,221}Bi$ calculated in HFB approach with Gogny forces D1S [Hi_HFB]. A clear change of the PES minimum can be noticed by moving to heavier isotopes.

This inference is further supported by the shell model calculations presented in Fig.4, performed with the H208 effective interaction [Na21]. They show that Bi's ground state becomes more mixed with the increase of neutron number.

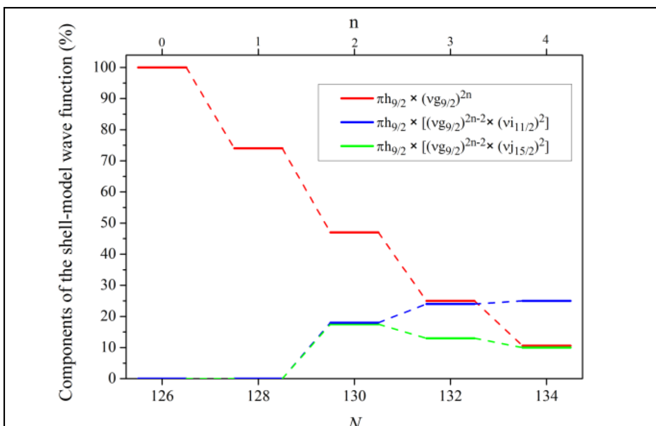

Fig. 4. The shell-model wave function components for the $I^\pi = 9/2^-$ gs of the even-N Bi isotopes. Only components with the weight larger than 10% are shown [Na22].

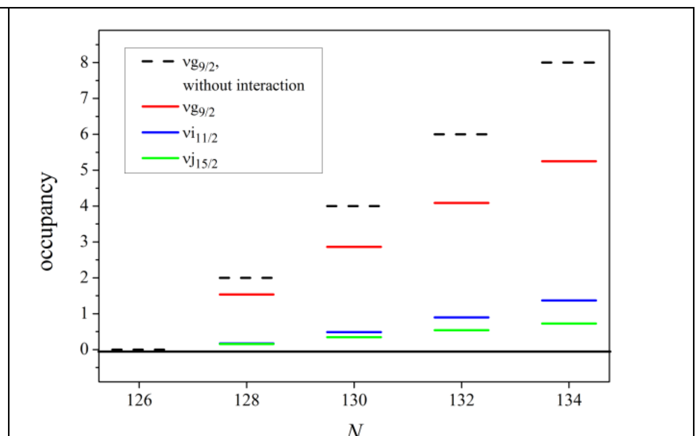

Fig. 5. The neutron shells occupancies for the $I^\pi = 9/2^-$ gs of the even-N Bi isotopes. Black dashed lines correspond to artificial situation with sequential $\nu g_{9/2}$ shell filling, while red/blue/green lines correspond to the inclusion of the effective interaction [Na22].

For example, a 100% pure $g_{9/2}$ neutron configuration is expected in ^{209}Bi, but its weight decreases quite fast by moving to the heavier isotopes, with the increase of the contribution from $\nu i_{11/2}$ and $\nu j_{15/2}$. Furthermore, Fig.5 shows the calculated occupancies of different neutron orbitals, in an unrealistic scenario of ‘no interaction’ (black lines) and with the inclusion of the residual interaction (red, blue and green lines). One clearly sees that with the realistic interaction included, the occupation of the $g_{9/2}$ orbital decreases (relative to ‘no interaction’ option) for the heavier Bi isotopes, while the occupation of higher-lying $i_{11/2}$ and $j_{15/2}$ orbital increases. The latter might also have a direct link to the discussion of the N=126 kink in neutron-rich isotopes, see Sec.II.1.

Therefore, to clarify on the aforementioned topics, we plan to measure for the first time the μ(^{219}Bi)-value and the quadrupole moments of ^{215,217}Bi, and re-measure magnetic moments of ^{215,217}Bi with improved accuracy.

In parallel with the IS/hfs measurements we will also obtain improved decay information for ^{219}Bi, which is poorly known presently. In particular, the half-life of this isotope will be measured to resolve the existing discrepancy: 8.7(2.9) s [Ca17], vs. 22(7) s [Be12].

3. OES at N ≥ 133 (^{216}Bi) as a tool to search for octupole effects in the ground states of the neutron-rich Bi isotopes.

As was mentioned above, the inverse OES may indicate the development of octupole collectivity [Ve19]. It should be noted that according to calculations in the framework of microscopic-macroscopic approach, a noticeable octupole deformation (with $\beta_3 \sim 0.1$) starts to develop from N = 132 (^{215}Bi) for the Bi isotopes [Mö03]. This effect might also be related to deviation of magnetic moments, described above (Fig.2).

To deeper understand the observed phenomena, we need to decrease uncertainty of $\delta\langle r^2\rangle$ in $^{215\text{-}217}$Bi to reliably establish the character of OES (normal or inverted) at N = 133 (^{216}Bi) and probe the OES at N = 135 (^{218}Bi) and N = 137 (^{220}Bi). The latter task requires the measurement of $\delta\langle r^2\rangle$ for ^{219}Bi, thus providing an additional reason for the measurements for this isotope.

III. Proposed measurements

1. **IS and hfs for the high-spin isomers in the N>126 Bi isotopes (7 shifts)**

We propose to study 3 long-lived high-spin Bi isomers, ^{212}Bi^{m2} [I^π = (18$^-$)], ^{212}Bi^{m1} [I^π = (8$^-$, 9$^-$)], and ^{213}Bi^{m} [I^π = (25/2$^-$)]. Magnetic moment values will help to validate the configuration assignment, whereas IS values will contribute to understanding of the kink in charge radii at N = 126. In parallel, we are planning to study decay of these isomers with IDS.

2. **IS and hfs for the ground state of $^{215\text{-}220}$Bi (7 shifts)**

We will reduce uncertainties for ^{215,216,217}Bi owing to better resolution provided by (PI-)LIST combined with injection-seeded, narrow-band laser for the first excitation step. Measurements of IS and hfs for ^{219}Bi will enable us to trace the behavior of μ(9/2$^-$) further away from the magic neutron number N = 126, and probe the OES at N = 135, while the IS data for ^{220}Bi will be helpful to estimate OES at N = 137. In parallel, we are planning to study nuclear decay of ^{219,220}Bi with IDS. In particular, the first investigation of excited states in the daughter ^{220}Po will be performed, including, possibly, the identification of the sub-μs 8$^+$ isomer in ^{220}Po. Such isomers were studied in our IS650 fast-timing investigation of ^{214,216,218}Po. This will also complement our recent first decay spectroscopy study of ^{220}Po in 2022 [Po_IS456].

IV. Experiment and yield estimates

1. Bi yield estimates

Table 1 summarizes the yields and beam time request of Bi isotopes to be studied. Yields were estimated using the ones observed during the RILIS IS608 and IS650 runs, with the necessary corrections, where needed, as explained below.

As the (PI-)LIST mode is requested for this run, to suppress the strong Fr isobaric contamination in the beams of ^{212,213,219,220}Bi, we need to account for the LIST yields reduction relative to the standard RILIS operational mode. From a series of measurements in 2022’ campaigns with the neutron-rich Tl, Po and Ac nuclei [Po_IS456, He22] we assume a factor of ~20 for this reduction. High resolution mode is expected to lead to an additional efficiency decrease by a factor of 2-5.

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^{π} = (18⁻)	420	6.1E+03	3.1E+02	3[a b]
212m1, I^{π} = (8⁻, 9⁻)	1500	5.5E+03	2.8 E+02	
213m, I^{π} = (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

Yields (Y) for ^{212,213,215}Bi were calculated by the formula:

$$Y(A) = Y(216)\frac{P(A)}{P(216)}, \qquad (1)$$

where P(A) is ABRABLA in-target production. Here we neglect difference in in-target decay due to different half-lives of ^{A}Bi and ^{216}Bi. This factor will increase Y(A) since $T_{1/2}$ (A)> $T_{1/2}$ (^{216}Bi) for A=212,213,215.
For ^{219,220}Bi we cannot use Eq. (1) due to shorter $T_{1/2}$ for these nuclei (~10 s, see Table 1) than that for ^{216}Bi (135 s). According to diffusion-effusion model the worse case when $T_{1/2} \ll t_{effusion}$ and $T_{1/2} \ll t_{diffusion}$ corresponds to decrease of the yield ~$(T_{1/2})^{3/2}$ [Ba22], thus the conservative estimation should be as given by Eq.2, which was used for yield estimation for ^{219,220}Bi:

$$Y(A) = Y(218)\frac{P(A)}{P(218)}\left(\frac{T_{1/2}(A)}{T_{1/2}(218)}\right)^{3/2} \qquad (2).$$

^{215}Bi isomer ratio Y(215m)/Y(215g)=0.02 was measured in [Ku03]. This value was now used also for ^{213}Bi since it is assumed that ^{213m}Bi has the same configuration as ^{215m}Bi.

The ratios of Y(212m1)/Y(212_total)=0.63 and Y(212m2)/Y(212_total)=0.24 were measured in [Ch13], in ^{238}U(670 AMeV)+Be projectile fragmentation. This reaction is expected to give similar yields as the p+^{238}U spallation reaction at ISOLDE. Keeping this in mind, we conservatively estimated isomer ratios in our case: Y(212m1)/Y(212_total)=0.3, Y(212m2)/Y(212_total)=0.1.

2. Estimated beam time necessary to execute the proposed program

We will exploit both the IDS and MR-ToF for hfs scanning. At IDS, β-delayed γ rays and/or α decay of the daughter Po isotopes will be monitored, as relevant to each Bi precursor. At present, IDS undertakes a substantial upgrade, which will allow up to 15 Ge Clover detectors to be used, instead of 4-6 in the previous configuration. The singles γ-ray efficiency of IDS in the range of 200-400 keV (where we expect the most intense decays) was ~10% (4-6 detectors), thus a total efficiency of 20-30% in the upgraded version can be reliably reached for decays involving high γ-ray multiplicity. Furthermore, high-spin/high-lying isomers in ^{212m1,m2}Bi decay by β-delayed α emission with uniquely high α-decay energies, which will also be used for hfs scanning along with γ rays. Improved α-decay IDS setup will provide an α-detection efficiency close to 20%.

As an example, we explain the beam time request estimation for ^{219}Bi. To determine its IS/hfs with sufficient accuracy we need ~20 counts in hfs maximum and ~50 laser frequency steps. With the typical γ-ray and α-decay efficiency of IDS (~20% each) one needs ~3 min per frequency step, thus 2.5 hours for a full scan. Hence, for a minimum number of two scans we need ~1 shift, considering additional time needed to search for unknown γ lines and determination of the scanning range. An additional shift will be devoted to decay spectroscopy of ^{219}Bi. The beam-time request for other isotopes was estimated by a similar procedure.

Ion-counting/hfs scanning with MR-ToF might be required/beneficial for the isomers with half-lives longer than a few minutes, where counting decays with IDS might become impractical. This method was used for several of our previous studies, no issues is expected here.

Based on our 2022's experience with Po/Ac PI-LIST operation, we also request 2 dedicated shifts for the PI-LIST tuning with the proton beam, to select best working parameters for the suppression of the Fr contamination, while keeping the good Bi/Fr ratio.

To summarize, we propose to study IS and hfs of $^{212m1,\ 212m2,\ 213m,\ 215,\ 216,\ 217,\ 219,\ 220}$Bi. The total beam time request: 13 shifts for measurements + 1 shift for the reference scans+2 shifts for the PI-LIST optimization, in **total 16 shifts**.

References

[An20] B. Andel et al., Phys. Rev. C **102**, 014319 (2020).
[An21] B. Andel et al., Phys. Rev. C **104**, 054301 (2021).
[Ba21] A.E. Barzakh et al., Phys. Rev. Lett. 127, 192501 (2021).
[Ba22] A.E. Barzakh et al., NIM B 513, 26 (2022).
[Be12] G. Benzoni *et al.*, Phys. Lett. B **715**, 293 (2012).
[Ca17] Caballero-Folch et al., Phys. Rev. C **95**, 064322 (2017).
[Ch08] L.Chen, PhD thesis, unpublished, Giessen, 2008.
[Ch12] L. Chen et al., Nucl. Phys. A 882 71 (2012)
[Ch13] L. Chen et al., Phys. Rev. Lett. **110**, 122502 (2013)
[Fr OES] I. Budinˇcevi´c *et al.*, Phys. Rev. C **90**, 014317 (2014); R. P. de Groote *et al.*, Phys. Rev. Lett. **115**, 132501 (2015).
[Da21] T. Day Goodacre, et al., Phys. Rev. Lett. **126**, 032502 (2021).
[Go13] P. M. Goddard, P. D. Stevenson, and A. Rios. Phys. Rev. Lett., **110**, 032503, 2013.
[Hi_HFB] S. Hilaire, M. Girod, https://www-phynu.cea.fr/science_en_ligne/carte_potentiels_microscopiques/carte_potentiel_nucleaire_eng.htm
[He22] R. Heinke, private communication
[Ku03] J. Kurpeta et al., Eur. Phys. J. A **18**, 31 (2003).
[Mö03] P. Möller, B. Pfeiffer, and K.-L. Kratz, Phys. Rev. C **67**, 055802 (2003).

[Mö12] P. Möller, A. J. Sierk, R. Bengtsson, H. Sagawa, T. Ichikawa, ADNDT **98** (2012)
[Na21] H. Naïdja, Phys. Rev. C, 103, 054303 (2021).
[Na22] H. Naïdja, private communication.
[NNDC] NNDC databases.
[Po_IS456] T. E. Cocolios et al., IS456 Addendum. http://cds.cern.ch/record/1642843/files/?ln=en.
[Ve19] E.Verstraelen et al, Phys. Rev. C 100, 044321 (2019).

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experiment will be performed at the ISOLDE Decay Station (IDS) with 2-4 Si detectors inside, and up to 15 Clover Ge detectors outside. IDS was successfully used in many experiments, therefore solid understanding of all possible hazards is available. We will use also usual IDS settings/detectors with the standard calibration sources. We will also install a magnetof system at LA1. RILIS operation is required tuned on Bi ionization.

Part of the Choose an item.	Availability	Design and manufacturing
IDS, magnetof at LA1 (not disturbing the IDS operation/tuning)	☒ Existing	☒ To be used without any modification
RILIS injection-seeded laser system	☒ To be set up	☒ Requires ~1 week setup time and availability of cw seed laser (e.g. from CRIS). CRIS agreed to provide/support this laser operation.

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed IDS installation.

Additional hazards:

Hazards	IDS	
Thermodynamic and fluidic		
Pressure	-	
Vacuum	Standard ISOLDE vacuum	
Temperature		
Heat transfer		
Thermal properties of materials		
Cryogenic fluid	LN2, 2 Bar, 150 l	
Electrical and electromagnetic		
Electricity	Standard power supplies	
Static electricity		
Magnetic field		

Batteries	☐	
Capacitors	☐	
Ionizing radiation		
Target material [C-foils]	Standard IDS tape	
Beam particle type (e, p, ions, etc)		
Beam intensity		
Beam energy		
Cooling liquids		
Gases		
Calibration sources:	☒ Standard alpha/gamma sources	
• Open source	☐	
• Sealed source	☐	
• Isotope	^{239}Pu, ^{241}Am, ^{244}Cm	
• Activity	1 kBq each	
Use of activated material:		
• Description	☐	
• Dose rate on contact and in 10 cm distance		
• Isotope		
• Activity		
Non-ionizing radiation		
Laser	Standard RILIS operation	
UV light		
Microwaves (300MHz-30 GHz)		
Radiofrequency (1-300MHz)		
Chemical		
Toxic	Pb shielding, 30-40 bricks	
Harmful		
CMR (carcinogens, mutagens and substances toxic to reproduction)		
Corrosive		
Irritant		
Flammable		
Oxidizing		
Explosiveness		

Asphyxiant		
Dangerous for the environment		
Mechanical .		
Physical impact or mechanical energy (moving parts)		
Mechanical properties (Sharp, rough, slippery)		
Vibration		
Vehicles and Means of Transport		
Frequency		
Intensity		
Confined spaces		
High workplaces		
Access to high workplaces		
Obstructions in passageways		
Manual handling		
Poor ergonomics		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): Negligible