EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Laser and nuclear decay spectroscopy study of the neutron-rich high-spin states in the ^{212,213}Bi isotopes with LIST

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Abstract

This is the resubmission of our proposal, which was initially submitted in winter 2023 (INTC-2023-003, INTC-P-649, https://cds.cern.ch/record/2845561) and requested 16 shifts for the laser and nuclear decay spectroscopy studies of $^{212,213,215-220}$Bi. Following the INTC recommendations, we now concentrate on the investigations of the high-spin isomers in ^{212,213}Bi only.

In 2016-2018, successful β-delayed fission and in-source laser spectroscopy campaigns (IS608) for many isotopes in the range of $^{187-218}$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 for the first time the changes in the mean-square charge radii ($\delta\langle r^2\rangle$) and electromagnetic moments of the high-spin isomers in ^{212,213}Bi. These results will help developing the microscopic understanding of the kink in the charge radii at N=126. Recently, several theoretical approaches were used by different groups to successfully describe the kink, but the underlying physics phenomena exploited were quite different. Our new data will probe these models via magnetic moments and $\delta\langle r^2\rangle$ measurements.

Earlier, the studies of ^{212,213}Bi isotopes were accepted by INTC within the initial IS608 program, but they were inaccessible in our previous experiments due to overwhelming contamination from the Fr and Ra isobars. We will overcome this obstacle by using the LIST,

which efficiently suppresses them, as was shown in our successful Tl [Yue24], Po and Ac runs in 2022. Further increase in sensitivity will be achieved by using enhanced detection capabilities provided by the upgraded ISOLDE Decay Station (IDS).

Requested shifts: **10 in one run with the LIST**

I. Introduction: Selected results from 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 submitted/in preparation for publications (#4-6 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. Similar to ^{214}Bi, an extensive β–γ spectroscopy (IS650) of the high-spin isomer with $I^{\pi} = (8^{-})$ in ^{216}Bi was completed, the manuscript will be submitted to PRC in January 2024 [An24].
5. 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).
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.

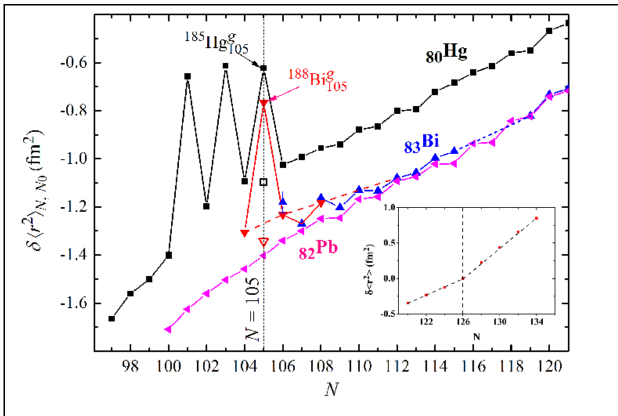

Fig. 1. Comparison of $\delta\langle r^2\rangle$ values for Bi, Pb and Hg isotopes [Ba21]. N_0 denotes the neutron number for the reference isotope within each chain. In the inset the kink in charge radii at N = 126 for Bi isotopes is shown, together with our IS608 data which establishes the near linear trend for $\delta\langle r^2\rangle$ values up to N=134.

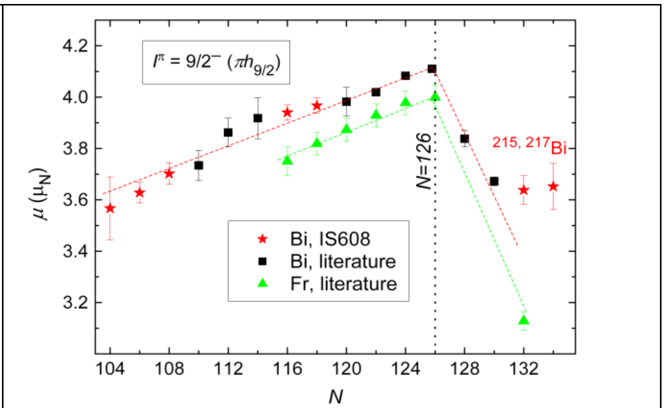

Fig. 2. Magnetic moments of $I^{\pi} = 9/2^{-}$ gs for Fr and Bi even-N isotopes. Points are connected by lines to guide the eyes. While there is a linear N dependence for the magnetic moments in ^{209,211,213}Bi, our preliminary data from IS608 for ^{215,217}Bi strongly deviate from this trend.

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 Tl/Po/Ac 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 link to the kink in Bi ground state charge radii at N=126.

The 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 experimental 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. While ^{212m1,213g}Bi involve only the $g_{9/2}$ neutrons ($[\pi h_{9/2}\times(\nu g_{9/2})^3]_{8,9^-}$ configuration for ^{212m1}Bi and $[\pi h_{9/2}\times(\nu g_{9/2})^4]_{9/2^-}$ for ^{213g}Bi), the proposed leading configurations for ^{212m2,213m}Bi presumably 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} $[\pi h_{9/2}\times((\nu g_{9/2})^2\times\nu i_{11/2})]_{18^-}$, ^{213}Bi^{m} $[\pi h_{9/2}\times (\nu g_{9/2}\times\nu i_{11/2})]_{25/2^-}$. The measurements of the magnetic moments for these states will allow to confirm (or reject) the proposed configurations.

The situation with the theoretical interpretation of the N=126 kink is also unclear, despite many studies performed for this important topic. Apart from the earlier theoretical studies (see e.g. [Ta93,Go13] and references therein), recently three different approaches attempting to describe the kink were applied, e.g. by using the Fayans energy density functional for the Pb and Sn chains [Fa20, Go19], or different versions of the relativistic or non-relativistic Hartree-Fock-Bogoluybov calculations in our Hg studies [Da21]. Importantly, while each approach describes the kink fairly well, they contradict each other concerning the origins of the kink. For example, "Fayans-based" method [Go19] put forward pairing (with gradient-density dependence) as the main explanation. Nakada, within non-relativistic HFB method [Na15,Da21] proposed the modification of the spin-orbital part of the interaction, whereas according to relativistic HFB by Afanasjev et al [Da21] the kink is determined by the details of underlying singe-particle structure. Furthermore, this study also suggested that the pairing effect is not important, in contrast to the results from [Go19].

Specifically, in several theoretical approaches, including our Hg study [Da21], it is both the position (relative to the $\nu g_{9/2}$ orbital) and the occupation of the $\nu i_{11/2}$ shell which determines the kink in the gs charge radii at N=126. 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. Therefore, the isomer shift for the high-spin states in ^{212,213}Bi will be a strong benchmark when comparing these theoretical approaches and underlying kink mechanisms. It is important, that we will study nuclei in close vicinity of the magic number (N=129, 130) where other effects, e.g. deformation, are expected to be small.

We are in touch with several theoreticians, e.g. A.Afanasjev, H. Nakada and I.Borzov, who provided strong and successful support of our previous studies of Hg and Tl isotopic chains [Da21,Yue24]. They are going to calculate isomer shifts in Bi isotopes in order to compare them with experiment and conclude what explanation of the shell effect in radii is closer to the reality.

Thus, the main goal 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 $I^{\pi} = (18^{-})$ isomer and the isomeric state with $I^{\pi} = (8^{-},9^{-})$ 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 isomers in ^{214,216}Bi [An21,An24].

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).

III. Proposed measurements: IS and hfs for the high-spin isomers in the ^{212,213}Bi isotopes

We propose to study IS and hfs for long-lived high-spin Bi isomers, ^{212}Bi^{m2} [$I^{\pi} = (18^{-})$], ^{212}Bi^{m1} [$I^{\pi} = (8^{-}, 9^{-})$], and ^{213}Bi^{m} [$I^{\pi} = (25/2^{-})$]. Their 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 the same scans ground states of $^{212,\,213}$Bi will be measured. Although their IS and hfs have been measured earlier, the study of gs and isomers simultaneously will exclude possible systematic uncertainties stemming from the wavemeter drift. In parallel, we are planning to study nuclear decay of these isomers with IDS.

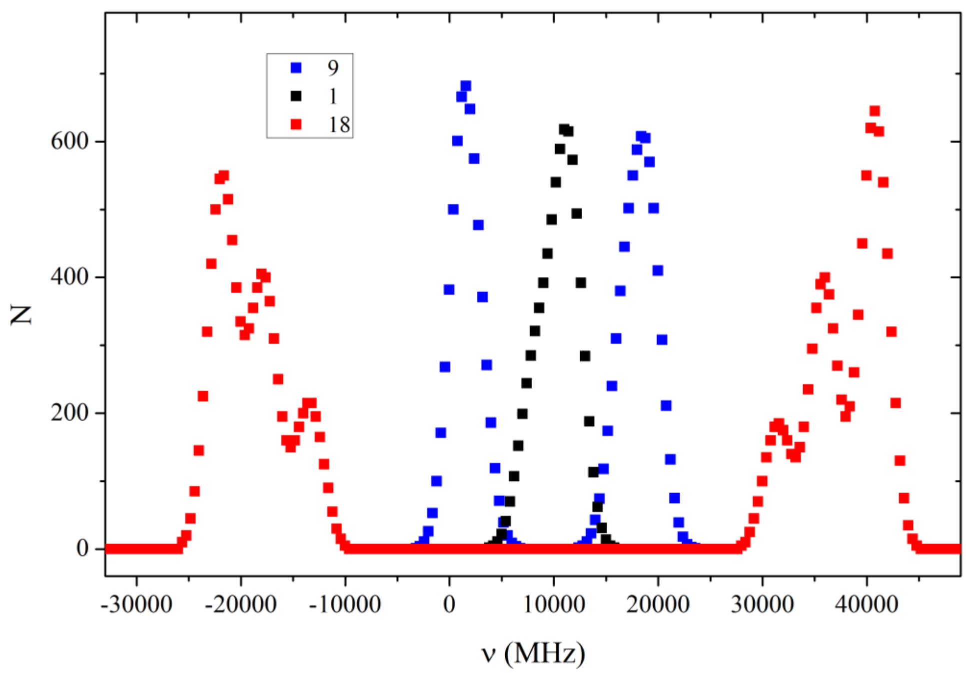

Fig. 3. Simulated hfs spectra for $^{212m1,\,212m2,\,212g}$Bi (I = 9, 18, 1 respectively).

In Fig. 3 the simulated hfs spectra for $^{212m1,\,212m2,\,212g}$Bi are shown. According to estimations, the isomer shifts in question are expected to be in the range of ~300-800 MHz. Typical uncertainty of isotope shift in standard RILIS in-source spectroscopy is ~50-100 MHz (with standard laser linewidth of 3.6 GHz).

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 LIST mode is requested for this run, to suppress the strong Fr isobaric contamination in the beams of ^{212,213}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.

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	$4^{a\ b}$
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	$3^{a\ b}$
216	135	1.0E+03 (IS650)	5.0E+01	
216m	396	1.5E+03 (IS608)[c]	7.5E+01	
209 Reference Faraday Cup scans		Multiple 0.5 h scans over the whole run		1
LIST optimization with the proton beam on target				1
Stable beam tuning to IDS/MR-ToF				1

[a]Scans of both isomers will be done simultaneously and require in total approximately 3 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 (see simulated hfs in Fig. 3).

[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}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.

^{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% in the upgraded version can be reliably reached. The γ–γ efficiency increase will be especially important for high γ-ray multiplicity events. 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%.

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 are expected here.

Based on our 2022's experience with Tl/Po/Ac LIST operation, we also request 1 dedicated shift for the 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 $^{212m1, 212m2, 212g, 213m, 213g}$Bi. The total beam time request: 7 shifts for measurements + 1 shift for the reference scans+1 shift for the LIST optimization, and 1 shift for stable beam tuning to IDS/MR_ToF, in **total 10 shifts**.

3. Link to the accepted LoI239 by G.Georgiev.

We mention that the LoI239 has 2 shifts for the test of production and purity of ^{210,212}Bi isotopes with the LIST, for their program of g-factors measurements for excited states in ^{210,212}Po, populated via beta decay of precursors. Provided our present proposal is accepted, we will perform these tests within our proposal, which will free those 2 shifts.

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1 Details for the Technical Advisory Committee

1 3.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: *ISOLDE Decay Station, ISOLTRAP MR-ToF-MS, RILIS*

☒ To be used without any modification

2 3.2 Beam production

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
$^{212-213}$Bi	>10^3, but will be reduced to around 10-10^2 by the LIST mode	10	~2-60 min

- Full reference of yield information: *Yields for 212,213Bi have never been measured yet, but we have extensive data for heavier Bi isotopes, and also for isobaric Po, as one example. This allows to reliably estimate the production rates.*

- Target - ion source combination: *UC_x + LIST*

- RILIS? *YES, in the LIST mode*

  ☒ Special requirements: *laser scanning*

- Additional features?

  ☐ Neutron converter:

  ☒ Other: *LIST mode*

- Expected contaminants: *Fr isotopes – will be strongly suppressed by LIST.*

- Acceptable level of contaminants: *Not sensitive to stable/long-lived contaminants.*

- Can the experiment accept molecular beams? *No*

- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of?

  Yes, the LoI239 by Georgiev has 2 shifts accepted for the rate/purity measurements for 210,212Bi. If the present proposal is accepted, we can perform these measurements, thus no need for these 2 shifts for LoI239 (this is confirmed with Georgi Georgiev, who is also a co-author on this proposal)

3 3.4 Shift breakdown

Summary of requested shifts:

With protons	Requested shifts
Target+LIST optimisation Reference laser scans Data taking, laser scans, ^{212}Bi Data taking, laser scans, ^{213}Bi	1 1 4 3
Without protons	Requested shifts
Tuning stable beam from GPS to IDS and MR-ToF	1

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose? *Energy and efficiency calibration of detectors.*
  - Isotopic composition? *^{137}Cs, ^{241}Am, ^{152}Eu, ^{133}Ba, ^{60}Co*
  - Activity? *<300 kBq, ISO standard calibration sources*
  - Sealed/unsealed? *Sealed*

- For collections:
  - Number of samples? *None*
  - Activity/atoms implanted per sample? *n/a*
  - Post-collection activities? *n/a*