

Call: 5.9/5.9.2/FAIR-RO

Project acronym: InCellMNT

FAIR Research Programme / Experiment: Super-FRS

## **Annual Summary Document\***

**Year: 2024**

Months: August – December

**Project Title: Experimental program of neutron rich isotope production using in-cell multi-nucleon reactions**

**Project Work Plan** (according to the contract)

**Stage: I. Preliminary and design studies**

**Activities:**

- I. 1. Experimental data analysis for isotopes in reaction  $^{238}\text{U}+^{209}\text{Bi}$
- I. 2. Development of the conceptual design of the HRU system
- I. 3. Development of the conceptual design of the MCP detector

**Allocated budget: 521.700 lei**

**Realized budget: 521.700 lei**

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\* Please fill in all the required items and do not alter the template

## 1. Cover Page (max 1 page)

The members of the InCellMNT project, listed in section 3, are involved in the study of exotic nuclei, especially in the neutron rich (n-rich) region, using radioactive ion beams generated via different nuclear reactions. Fragmentation of heavy ions and fission induced by high energy photons or light ions are among them. This research area is one of the most active in contemporary nuclear physics because it provides the main means to answer some of its most important questions: what are the processes responsible for the element synthesis in explosive stellar environments? what is the evolution of nuclear shell structure towards the limits of stability? which are mechanisms for that drive shape phase transitions? how does the nuclear equation of state depend on isospin?

The main goal of the project is to establish an exploratory experimental program aiming to open a new direction of research for the production and study of heavy  $A = 160-250$  n-rich isotopes by using Multi-Nucleon Transfer (MNT) reactions inside the Cryogenic Stopping Cell (CSC) of the FRS Ion Catcher (FRS-IC) facility at GSI. The addition of MNT to the standard fragmentation and fission reactions is expected to significantly improve the reach of radioactive ion beam (RIB) facilities towards the r-process path.

Analysis of the data obtained during the experiment G-22-00117, performed in May 2024, has provided the proof-of-principle measurement that this program is feasible. Concretely, MNT products along the  $A = 211$  isobaric chain have been identified and counted by the mass spectrometer of FRS-IC. Additionally, beam energy scans, performed by varying the thickness of the FRS energy degraders, have further supported the interpretation of the reaction products as fragments from the MNT reaction. The first results from this analysis have been submitted to publication as conference proceedings, while the full analysis will be soon reported in a full research article. Two oral presentations at an international symposium and an international workshop have also been given.

Apart from the above MNT measurement, evaluation of the data obtained during the beam intensity scan led to the conclusion that the isotope extraction efficiency is independent of the beam intensity on target in the  $10^5-10^6$  ions/s range. This is proof that the existing space charge containment system holds up to these values, an important step towards the target intensity of  $10^7$  ions/s expected at FAIR.

Another direction for the data analysis involves identifying and counting with the mass spectrometer of FRS-IC of the  $^{252}\text{Cf}$  spontaneous fission fragments. Due to the availability of precise measurements on fission fragment yields in the literature in this case, this type of measurements allows for a detailed characterisation of the experimental setup efficiencies. This analysis has started and a first set of results, including broadband mass measurements and an analysis of the nuclear phase shape transition around  $N = 90$ , has been submitted for publication as a full research article. The derivation of the CSC stopping and extraction efficiencies, which is needed for isotope production cross sections, is being currently investigated.

On the technical development component of the InCellMNT project, major advances have taken place. The design of the Helium Recovery Unit, which will recirculate and purify continuously the Helium gas, is expected to be completed at the beginning of 2025. Its construction and installation are scheduled to take place by the end of next year, with testing and commissioning activities planned for the last year of the project. The ion detector for the upgrade of the MR-ToF spectrometer has been identified and purchased, together with all the data acquisition and powering electronic modules that complete the detection system.

## 2. Scientific accomplishments (max 3 pages)

The main goal of the project is to develop a new research program at the FRS-IC facility at GSI that uses MNT reactions to drive RIBs and study neutron-rich isotopes selected from these beams. The first stage of this program started with experiment G-22-00117 [1], which took place during 24-27 May 2024. It used a  $^{238}\text{U}$  beam at 500 MeV/u, slowed down by degraders inside FRS to  $\sim 13$  MeV/u, on a  $49\text{ mg/cm}^2$   $^{209}\text{Bi}$  target with a back holder polyester layer of  $17.3\text{ mg/cm}^2$  thickness in the target wheel of INCREASE. A 2 mm Al degrader plate was placed inside the CSC before the target for final adjustments.

The main activity of the InCellMNT project in 2024 was the preliminary data analysis of the above experiment. Considering the characteristic beam energy dependence of the MNT process [2], with a fast onset above the Coulomb barrier followed by a steady decrease of the isotope production cross section, its first signature was searched in a scan of the beam energy on target at two settings of the beam degrader thicknesses. As shown in Figure 1, MNT target-like fragments (TLFs) along the  $A = 211$  isobaric chain start being counted by the multiple-reflection time-of-flight (MR-ToF) mass spectrometer once this thickness decreases below  $1700\text{ mg/cm}^2$ , a value confirmed by Mocadi simulations to correspond to the Coulomb barrier region.

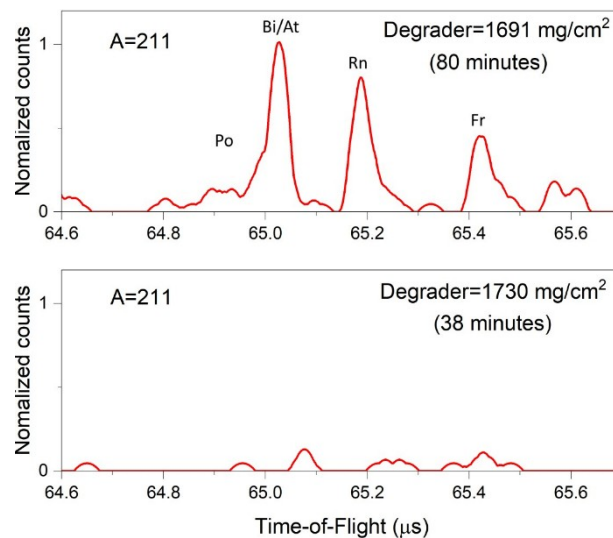


Figure 1. The MNT products identified by MR-ToF at  $A = 211$  with an optimal degrader thickness (top) and a non-optimal degrader thickness (bottom) for the  $^{238}\text{U}+^{209}\text{Bi}$  reaction [3].

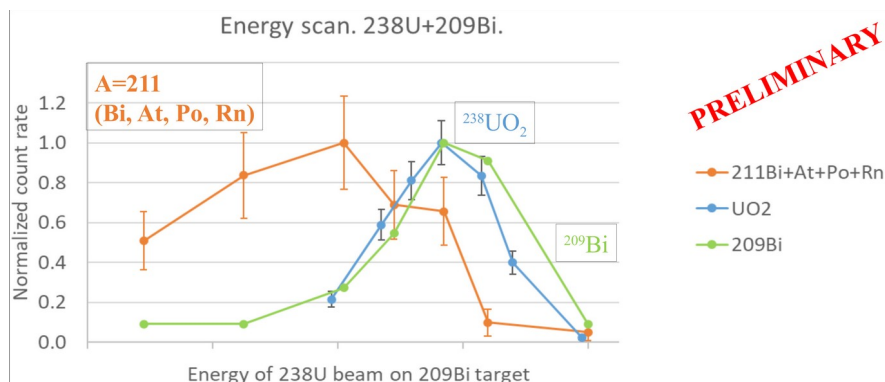


Figure 2. Normalized count rate with the MR-ToF mass spectrometer versus beam energy (FRS degrader thickness) for: primary beam extracted as  $\text{UO}_2$  (blue circles), elastically scattered target ions (green circles), identified  $A=211$  TLF isobars Bi, At, Po, and Rn (orange circles).

A detailed analysis of the degrader thickness scan, which results in a scan of the beam energy on target, was the next step of this analysis and is shown in Figure 2 together with identified beam ions (extracted as  $\text{UO}_2$ ) and elastically scattered target ions. This energy dependence (discussed above) and angular dependence (imposed by the beam dump blocking the forward angles) is characteristic to MNT reactions. Note also that the target-like channels are less affected by background reactions than projectile-like channels. The result in Figure 1 is submitted to publication as conference proceedings [3], while the full analysis will be submitted as research article [4]. Together, they constitute the main result of the project during stage I (year 2024).

The crucial outcome of the G-22-00117 experiment is the proof-of-principle measurement of MNT-driven RIBs with successful extraction, transport and identification by the MR-ToF. Another important outcome is that the beam intensity was varied during these measurements, leading to intensities on target in the  $10^5$ - $10^6$  ions/s range, and no efficiency decrease was observed. Therefore, the space charge containment system of INCREASE [5] works at least up to these values, which was the main technical challenge of the program. Another conclusion of the beam intensity scan is that intensities of the MNT-driver beam around 200 fA are sufficient to generate secondary RIBs with the FRS-IC facility. This is 5-6 orders of magnitude lower than the intensities used in MNT experiments at the KISS (RIKEN) and JYFL (Jyväskylä) and emphasizes the advantages of the experimental method developed for this program.

An important activity is the use of radioactive sources with well-known isotope production yields, such as a  $^{252}\text{Cf}$  spontaneous fission source, to characterize the stopping and extraction efficiencies of the setup. Combined with the beam properties on target, they allow for the derivation of isotope production cross sections in MNT reactions from the measured isotope rates with the MR-ToF spectrometer. A significant progress has been made in this analysis, as shown in Figure 3. Simultaneous, broadband, high-precision direct mass measurements of neutron-rich nuclides in the element range from barium to europium, produced by the spontaneous fission of  $^{252}\text{Cf}$ , have been analysed and submitted to publication as research article [6]. These nuclear mass measurements over a wide region of lanthanides were used to investigate the nuclear shape phase transition near  $N = 90$ . The work for the setup efficiencies using radioactive sources will continue.

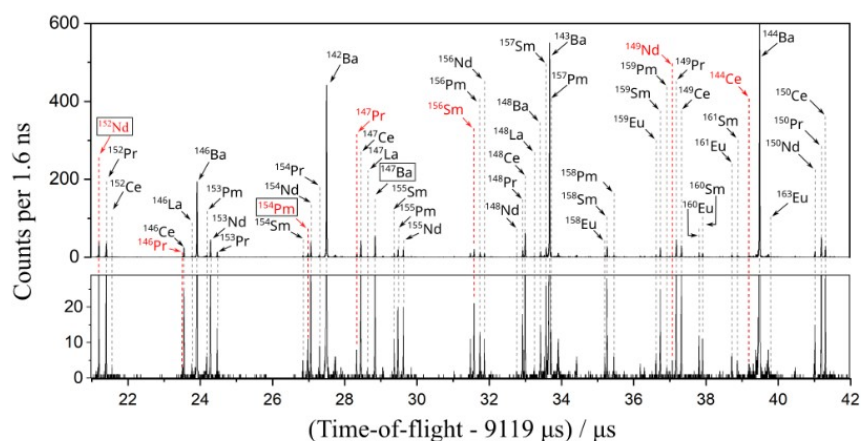


Figure 3. The TOF spectrum of neutron-rich nuclei produced in spontaneous fission of  $^{252}\text{Cf}$ . The upper part shows the full spectrum and the lower part shows a zoom in the ordinate for a better display of low-intensity peaks. Labels at the individual peaks indicate the identification [6].

On the technical side of the InCellMNT project, two developments were proposed: the development of a dedicated gas recirculation and purification system, called the Helium Recovery Unit (HRU), and an upgrade of the ion detector placed at the focal point of the MR-ToF spectrometer using the Multi-Channel Plate (MCP) technology.

The HRU system is necessary to maintain and control the high gas density and purity required for ion catchers with electric ion transport, such as the ones at the current FRS-IC and future Super-FRS facilities, over extended running periods. Its conceptual design has reached an advanced development stage over the last months. Specifically, the main components have been identified and their optimal operational parameters have been established. These components are the gas supply equipment; the vacuum pumps at the inlet of the HRU; the compressor unit with vacuum and pressure receivers; the pumping equipment for vacuum and gas exhaust; the gas purification devices; the automatic control hardware and software; the overall mechanical design and frame assembly. A mock-up of the HRU conceptual design is shown in Figure 4. The gas recovery system i.e., the pumping system that extracts the gas from the extraction chamber must provide a controllable pumping speed between 150 to 250 m<sup>3</sup>/h at an extraction chamber pressure of 1-10 mbar. The compressor works with two buffer vessels, shown in red in the right panel of Figure 4, one over pressure (4 bar, 250 l) and one under pressure (0.8 bar, 150 l).

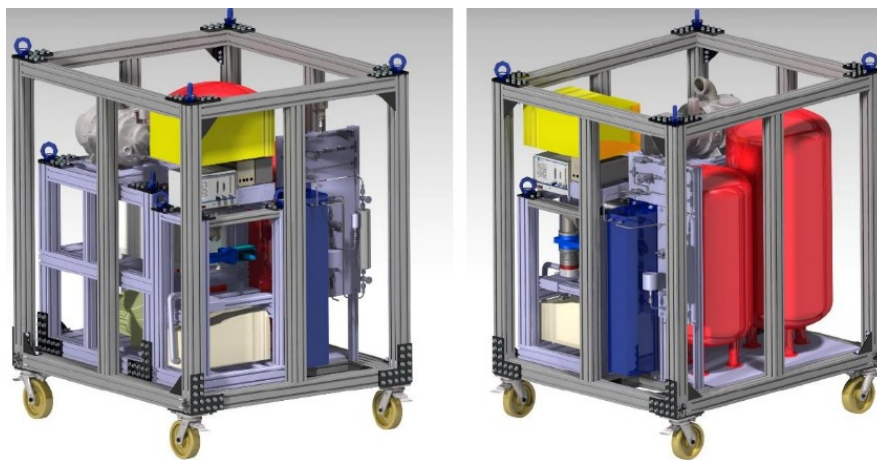


Figure 4. Conceptual design of the HRU setup.

The activity to design and customize an MCP ion detector for the upgrade of the MR-ToF spectrometer has passed the first milestone: identification and acquisition of the suitable detector and electronics. A two-dimensional delay-line MCP type DLD40EP from the manufacturer RoentDek Handels GmbH (Germany) has been purchased, together with the data acquisition and powering equipment: multi-event time digitizer MCS8AGOLD (80 ps resolution, 12.5 GHz rate) from FastComTec (Germany), high precision high power (EHS 44100n) and low power (EBS C005) sources from ISEG (Germany), UHV feedthroughs, and various connectics and mechanical parts. This detection system is able to provide multi-particle hits and analyse both time and two-dimensional position for each individual hit with state-of-the-art performance: temporal resolution 55 ps (RMS), spatial resolution 55  $\mu$ m (RMS), “double-hit” dead time below 15 ns. They will allow for extended functionalities, apart from the main one of providing the ion time-of-flight stop signal, such as two-dimensional beam scans and shape analyses. The further developments at the IFIN-HH laboratories necessary to commission the MCP system are described in section 7.

#### References:

- [1] P. Constantin, T. Dickel, et al., experiment proposal G-22-00117 to GSI G-PAC (2022).
- [2] P. Constantin, et al., *Physica Scripta* 99, 075313 (2024).
- [3] A. Mollaebrahimi, P. Constantin, et al., *Nuclear Physics A* 1057, 123041 (2025).
- [4] A. Shraier, P. Constantin, et al., to be submitted to *European Physical Journal A*.
- [5] A. Rotaru, et al., *Nuclear Instruments and Methods B* 512, 83 (2022).
- [6] A. Spataru, P. Constantin, et al., *Physical Review C* 111, 054307 (2025).

### 3. Group members (table)

No.	Name	Role	FTE <sup>†</sup>	PhD/Master students
1	Paul Constantin	Project Director	512	
2	Dimiter L. Balabanski	Senior Researcher	0	
3	Alexandru N. State	Team member	0	
4	Adrian Rotaru	Team member	0	
5	Anamaria Spataru <sup>(1)</sup>	Team member	0	
6	To be employed <sup>(2)</sup>	Team member	0	PhD student

<sup>(1)</sup> Dr. Spataru has ended her employment at IFIN-HH in September 2024.

<sup>(2)</sup> A PhD position is opened within our team.

### 4. Deliverables

- Research Articles:
  - 1) A. Spataru, P. Constantin, et al., published in Physical Review C.
  - 2) A. Shraier, P. Constantin, et al., to be submitted to European Physical Journal A.
- Conference proceedings:
  - 1) A. Mollaebrahimi, P. Constantin, et al., published in Nuclear Physics A.
- Talks at conferences and workshops:
  - 1) P. Constantin: talk at the International Symposium on Nuclear Science (ISNS-24), Sofia, Bulgaria, 9-13 September 2024.
  - 2) A. Rotaru: talk at the International Symposium on Nuclear Science (ISNS-24), Sofia, Bulgaria, 9-13 September 2024.
  - 3) P. Constantin: two talks at the Super-FRS Collaboration Meeting, Moerfelden-Walldorf, Germany, 30 October - 1 November 2024.

### 5. Further group activities (max 1 page)

The MNT program at the FRS-IC facility, part of the Super-FRS experimental collaboration at FAIR, is a wide collaboration of more than 50 researchers from more than 10 countries. This is conducive for a strong research program of the IFIN-HH experts, allowing them to engage in top level R&D programs with international partners.

The development of advanced research capabilities of the InCellMNT group will allow its members to take leadership roles in the future developments at national level, such as the RIF at IFIN-HH facility. This program will build the first RIB facility in Romania, using the technologies and collaborations developed within the InCellMNT project, such as cryogenic stopping cells, ion catchers with electric transport, multi-reflection time-of-flight mass spectrometers and separators.

The hiring and training of new students, both at the graduate and undergraduate level, is very important in order to maintain a vibrant and future-oriented research environment. The InCellMNT project has recently hired a new doctoral research assistant who will become involved in the activities described here at the beginning of 2025.

### 6. Financial report (budgeted usage) for the reporting period (Annex)

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<sup>†</sup> Total number of hours (for a certain period) = 170 average monthly hours x number of months (e.g., for a full year: 170 hours/month x 12 months = 2040 hours)

## 7. Research plan and goals for the next year (max 1 page)

The main goal for 2025 remains the analysis of the data acquired during the 2024 campaign. This comprises the MNT data of experiment G-22-00117 and the  $^{252}\text{Cf}$  data for the characterisation of the FRS-IC setup. The identification and counting with the MR-ToF spectrometer of the TLF isotopes from the  $^{238}\text{U}+^{209}\text{Bi}$  is in an advanced stage and will be submitted to publication at the beginning of 2025. The identification and counting of the projectile-like fragments (PLFs) from the same reaction, and in particular of n-rich actinides, will need a more careful analysis, expected to extend over several months. This is due to the additional background sources in these output channels. One such background is generated by Xe isotope impurities ( $A/q\sim 128-132$ ) present in the CSC gas, which overlap with actinide PLFs extracted as doubly charged oxides at  $A/q\sim 127-135$ . Another background comes from nuclear reactions of the  $^{238}\text{U}$  beam in other CSC structures. Finally, after the above identification and counting analyses are finished, the last stage is the extraction of the isotope production cross sections by combining them with the efficiency results of the  $^{252}\text{Cf}$  analysis and the evaluation of the beam intensity on target.

A new experimental proposal, entitled “Next stage of MNT driven neutron-rich isotope studies at the FRS Ion Catcher” by P. Constantin, S. Bagchi, T. Dickel et al., will be submitted during the current call of the GSI G-PAC for experiments during the 2026-2027 campaigns. It advances the next stage of the MNT program and comprises a technical run, improves upon the existing methods and technologies, and a physics run, which measures about 20 new n-rich actinide isotopes produced in the  $^{238}\text{U}+^{238}\text{U}$  MNT reaction. They will provide crucial data in a region with scarce experimental coverage and significant theoretical discrepancies of nuclear structure models.

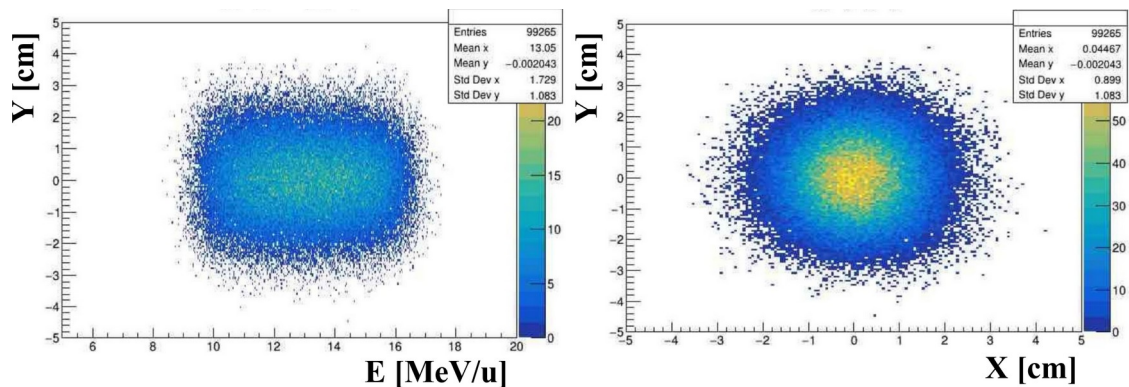


Figure 5. Mocadi simulation of 200 MeV/u  $^{238}\text{U}$  beam profile on INCREASE target produced by a gas degrader in S4 and an Al layer in CSC.

One of the issues that arose during the 2024 campaign was that the drive of the FRS beam degrader was broken. This was solved by using another degrader located 4 m upstream. The use of a non-optimal degrading system has led to broader beam energy spread and spot size on target. MOCADI simulations, shown in Fig. 5, provided the optimal degrader system made from a gas degrader in S4 and a thin Al layer before the target which will be built for this new experiment.

The HRU system design will be finished at the beginning of 2025 and the rest of the year will be dedicated to its construction and installation at GSI. The MCP ion detector system has been designed and all its components purchased. The activities scheduled for 2025 are the integration of its mechanical design inside the CAD of the MR-ToF spectrometer, the simulations with the SimIon software of ion trajectories accelerated by various voltage settings of the focusing electrodes (the DLD40 detector has maximum detection efficiency around 1 keV/u) and the integration of the DLD40 data acquisition software within the existing MR-ToF DAQ. A series of short test runs using ion sources and a vacuum chamber will benchmark the parameters of the MCP system before its shipment to GSI, where it will be installed.

## Financial Report

according to the regulations from H.G. 134/2011

		lei	
Type of expenditures		Year/ Whole period	
		Value	
		Planned	Realized
<b>1</b>	<b>PERSONNEL EXPENDITURES</b> , from which:	<b>92.976,00</b>	<b>61.641,00</b>
	1.1. wages and similar income, according to the law	90.930,00	60.284,00
	1.2. contributions related to wages and assimilated incomes	2.046,00	1.357,00
<b>2</b>	<b>LOGISTICS EXPENDITURES</b> , from which:	<b>353.932,00</b>	<b>410.582,95</b>
	2.1. capital expenditures	348.932,00	393.864,93
	2.2. stocks expenditures	5.000,00	15.825,52
	2.3. expenditures on services performed by third parties, including:	0,00	892,50
<b>3</b>	<b>TRAVEL EXPENDITURES</b>	<b>30.000,00</b>	<b>13.815,70</b>
<b>4</b>	<b>INDIRECT EXPENDITURES – (OVERHEADS) *</b>	<b>44.792,00</b>	<b>35.660,35</b>
<b>TOTAL EXPENDITURES (1+2+3+4)</b>		<b>521.700,00</b>	<b>521.700,00</b>

\* Specify the rate (%) and key of distribution (excluding capital expenditures): 35,75% from (1+2.2+2.3+3)

To be filled in for:

- the project leader;
- for each of the partners (if any);
- for the whole project.