

Call: 5.9/5.9.2/FAIR-RO

Project acronym: InCellMNT

FAIR Research Programme / Experiment: Super-FRS

Annual Summary Document¹

Year: 2025

Months: January – December

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

Project Work Plan (according to the contract)

Stage: II. Fundamental characterization studies

Activities:

- II. 1. *Experimental data analysis for relative rates in reaction $^{238}\text{U}+^{64}\text{Ni}$*
- II. 2. *Experimental data analysis for the calibration with radioactive sources*
- II. 3. *Development of the HRU slow control system*
- II. 4. *Simulation of the electric and mechanic MCP systems*

Allocated budget: 471.700 lei

Realized budget: 471.700 lei

¹ Please fill in all the required items and do not alter the template

1. Cover Page (max 1 page)

The main activity directions of the InCellMNT project are related to the production and study of neutron-rich heavy (mass number region $A=150-250$) isotopes at the FRS Ion Catcher (FRS-IC) facility at GSI (Germany) using the nuclear reactions of multi-nucleon transfer (MNT) and spontaneous fission (SF). The long term goal of the project is the preparation of this research program for extension at the FAIR facility at GSI which will become operational after 2027.

The analysis of the data obtained during the experiment G-22-00117, performed in May 2024, has continued in 2025 in two directions. The first was an extension of the study performed in 2024 of the beam energy scans [1] included detailed comparisons with the beam transfer and elastic scattering channels, as well as advanced background evaluation. The second direction looked into a different data set, with high statistics at the optimal beam energy, in order to extract the isotope production rates as function of the nuclear mass and charge numbers. These results will be submitted soon for publication [2] and have been presented at the yearly Super-FRS collaboration meeting. Note that the analysis of the target-like fragments (TLFs) of the $^{238}\text{U}+^{209}\text{Bi}$ was established experimentally as the better way of validating this research program and has replaced the initially proposed $^{238}\text{U}+^{64}\text{Ni}$ reaction.

The analysis of the ^{252}Cf spontaneous fission fragments [3] done in 2024 has been complemented in 2025 with an extended survey of the atomic masses and a detailed theoretical calculation of the shape phase transition around $N = 90$ using the S-HF-BCS model described below. The comparison between the experimentally calculated and theoretically derived two-neutron separation energies S_{2n} has allowed a precise evaluation of the neutron and proton pairing strengths G_n and G_p in this region of the nuclide chart.

After the completion of the technical design of the Helium Recovery Unit (HRU) last year, a series of implementation activities have been started, in coordination with the groups at the GSI institute and at the Giessen University, in order to finish this project in 2026. Examples include work on the CAD and manufacturing files, definition of the requirements for the service systems (electric, vacuum, compressed air, etc.), compilation of technical specifications for the acquisitions, writing and testing the automatization and control software. The team of the InCellMNT project is involved in all these ongoing activities which are expected to conclude by the Spring of 2026, leaving the final testing and commissioning activities for the rest of next year.

The Micro-Channel Plate (MCP) ion detector for the upgrade of the MR-ToF mass spectrometer (MR-TOF-MS) has been configured as a 2-dimensional delay-line detector type DLD40 and purchased last year. In 2025, we have completed the mechanical design of this equipment which will allow for its mounting and powering inside the existing vacuum chamber of the FRS-IC facility.

The new experimental proposal G-24-00274, entitled “Next stage of MNT driven neutron-rich isotope studies at the FRS Ion Catcher” by P. Constantin, S. Bagchi, T. Dickel et al., has been ranked A+ by the G-PAC and granted 13 main shifts during 2027. Several activities have been started to prepare for this new experiment: manufacturing of a new target made from a U-Mo alloy, design and installation of a new degrader system, design and installation of radiation shielding around the FRS-IC central systems, and others.

2. Scientific accomplishments (max 3 pages)

The preliminary data analysis of the G-22-00117 MNT experiment [1] done in 2024 has been expanded this year. Figure 1 shows eight TLF isotopes (outlined in orange) with mass numbers $A = 210$ and 211 identified with a FWHM resolution of $\tau=30$ ns. These MR-TOF-MS spectra were acquired in 449 isochronous turns with a total time of flight in the analyzer of $t=20010$ μ s, leading to a mass resolving power of $m/\Delta m = t/(2\tau) \approx 3.3 \cdot 10^5$. The region outside these peaks (outlined in blue) is made by background from molecular ion contamination. Its systematics as function of the degrader thickness scan allows for a precise characterization and subtraction of the background level.

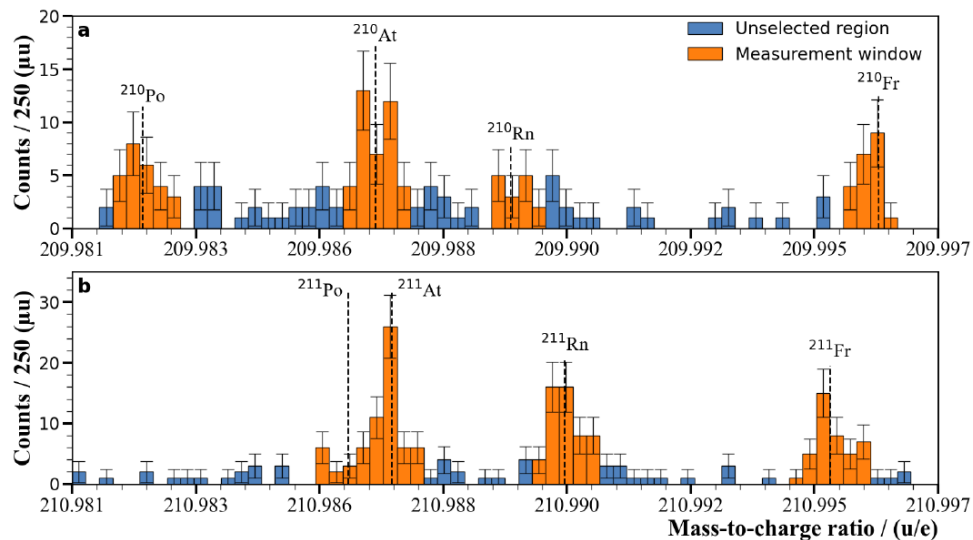


Figure 1. MR-TOF-MS mass-to-charge ratio for reaction products with mass numbers $A = 210$ (upper panel) and $A = 211$ (lower panel). The dashed vertical lines mark the literature mass values of the isotopes.

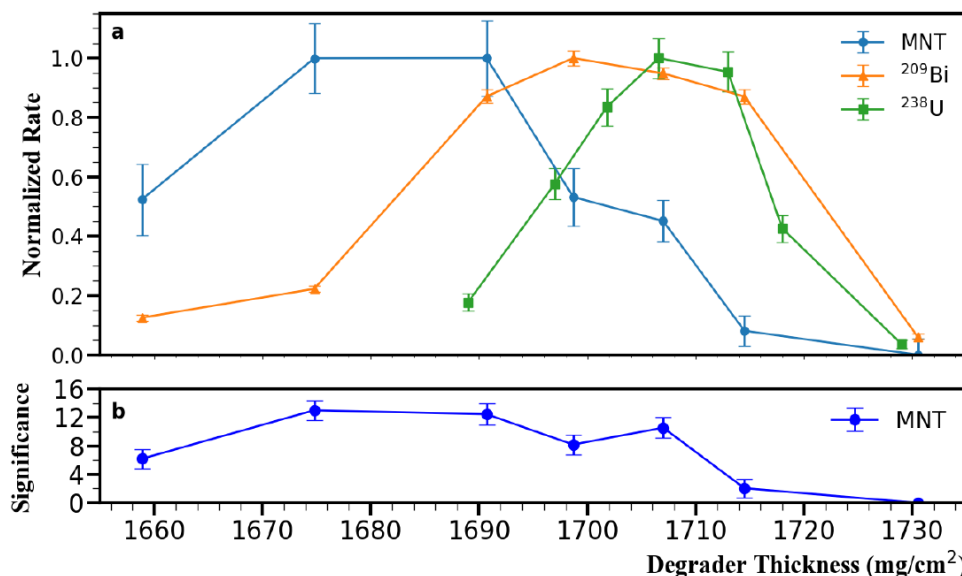


Figure 2. Upper panel: background-subtracted rates of ^{238}U (green squares), ^{209}Bi (orange triangles), and the MNT candidates (blue circles), each normalized to their respective maximum values. The MNT candidates represent the summed yields of the mass numbers shown in Fig. 1. Lower panel: the statistical significance of the MNT counts, calculated using Eq.(6). Connecting lines between

points in all panels are included for visual guidance and do not represent interpolated values between data points.

The upper panel of Figure 2 shows the dependence on the degrader thickness, hence on the beam energy on target, of the normalized rates of MNT reaction products (in blue), together with that of the elastically scattered ^{209}Bi ions (in orange) and of the ^{238}U beam ions that penetrate the target. The lower panel shows the statistical significance of the MNT signal relative to its background, quantified via the Poisson log-likelihood ratio test.

In parallel, the analysis of another data run of this experiment, containing high statistics at the optimal thickness has been analyzed to obtain the isotope production rates as function of the nuclear mass and charge numbers A and Z . These result represents the first measurement of broad range MNT secondary beams produced with energy degraded relativistic primary beams and will be soon submitted for publication [2].

Nuclide	Measured atomic mass (amu)	Mass excess (keV/c ²)		ΔME (keV/c ²)	σ deviation from Literature
		Measured	Literature		
^{157}Eu	156.925424(54)	-69467(51)	-69459(4)	-8(51)	-0.16
^{153}Sm	152.922112(60)	-72552(56)	-72560.1(10)	8(56)	0.14
^{156}Sm	155.925555(20)	-69345(19)	-69361(9)	16(21)	0.78
^{151}Pm	150.921234(57)	-73370(53)	-73386(5)	16(53)	0.29
$^{154}\text{Pm}^*$	153.926678(25)	-68299(23)	-68267(25)	-32(34)	-0.94
^{147}Nd	146.916216(76)	-78045(70)	-78146.8(10)	102(70)	1.45
^{149}Nd	148.920194(26)	-74339(24)	-74375.5(21)	37(24)	1.50
^{151}Nd	150.923854(25)	-70930(23)	-70943.2(11)	13(23)	0.58
^{152}Nd	151.924711(16)	-70132(15)	-70150(24)	18(28)	0.66
^{145}Pr	144.914507(25)	-79636(24)	-79626(7)	-10(25)	-0.40
^{146}Pr	145.917596(58)	-76759(54)	-76670(30)	-89(62)	-1.44
^{147}Pr	146.918979(23)	-75470(21)	-75444(16)	-26(26)	-0.99
^{144}Ce	143.913613(19)	-80469(18)	-80431.9(28)	-37(18)	-2.06

Figure 3. Measured atomic mass and mass excess values of nuclides, where the reported measurements represent the first direct mass measurements. The values are compared with the literature values ME_{lit} , which refers to the values given in AME20 based on previous indirect mass measurements. The ΔME marks the deviation of the measured mass excess values from the literature. The deviation in sigma with respect to the literature is shown in the last column.

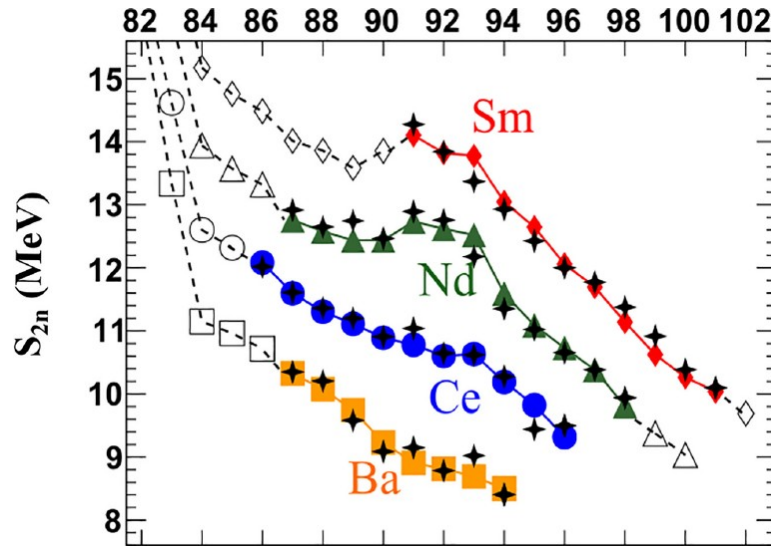


Figure 4. Evolution of the measured and theoretical S_{2n} values. The full, colored data points (connected by solid, colored lines) depict the experimental results, while the open symbols

(connected by dashed lines) are derived from tabulated values of AME20. The black crosses represent the theoretical results elaborated in this work.

The second activity in 2025 was finishing and publishing the analysis of the systematic mass measurement in ^{252}Cf spontaneous fission. After the main part of the experimental analysis was done in 2024, the work continued this year on two levels in order to interpret the results. The first one involved a comparison of the measured atomic masses with those existing in the literature, which is shown in Figure 3. The second one used detailed theoretical calculations of the shape phase transition around $N = 90$ using a Skyrme interaction Hartree-Fock (S-HF-BCS) model. They allowed for the extraction of the neutron and proton pairing strengths G_n and G_p in this region of the nuclide chart. A comparison of the experimental and theoretical two-neutron separation energies S_{2n} is shown in Figure 4. The results of the ^{252}Cf analysis has been published [3].

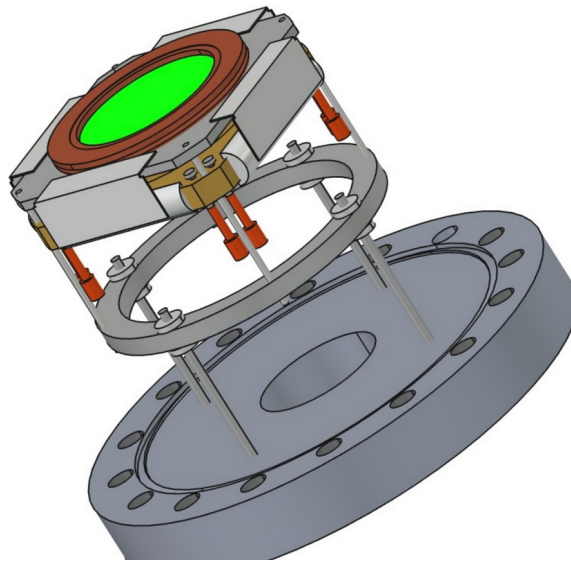


Figure 5. The MCP detector (in green) fixed on its holder plate by ceramic rings (in brown) and connected to delay-line anodes (in red). The holder plate stays on a mounting ring fixed on a mounting flange with an FT12 feedthrough for connections.

After the configuration and acquisition of the MCP ion detector in 2024, the next task was to design its mechanical structure with the goal to allow its mounting and powering inside the existing vacuum chamber of the FRS-IC facility. Due to the multiple high-voltage connectors needed by the DLD40-type MCP, a special feedthrough is needed on the mounting flange. The DLD40 detector is shown with green in Figure 5, together with the holder rings, delay-line anode and other mounting structures.

The technical work performed in 2025 was complemented by several tasks related to the implementation of the HRU unit established by the technical design completed last year. These ongoing activities, performed jointly with the teams from GSI and Giessen University, refer to the development of CAD and manufacturing files, definition of the requirements for the service systems (electric, vacuum, compressed air, etc.), compilation of technical specifications for the acquisitions, writing and testing the automatization and control software, and other.

References:

- [1] A. Mollaebrahimi, P. Constantin, et al., Nuclear Physics A 1057, 123041 (2025).
- [2] A. Shraier, P. Constantin, et al., to be submitted to European Physical Journal A.
- [3] A. Spataru, P. Constantin, et al., Physical Review C 111, 054307 (2025).

3. Group members (table)

The new project team, according to the additional act no. 1 to the contract is:

No.	Name	Role	FTE ²	PhD/Master students
1	Paul Constantin	Project Director	790	
2	Dimiter L. Balabanski	Senior Researcher	0	
3	Alexandru N. State	Team member	804	
4	Adrian Rotaru	Team member	752	
5	Midhun Cherumukku	Team member	264	
6	Kabita Kundalia	Team member	240	
7	Emil Udup	Team member	152	
8	Arunima Thekku Veetil	Team member	0	

4. Deliverables

- Research Articles:
 - 1) A. Spataru, P. Constantin, et al., Physical Review C 111, 054307 (2025); DOI: <https://doi.org/10.1103/PhysRevC.111.054307>.
 - 2) D. Amanbayev, et al., European Physical Journal Special Topics 234, 861 (2025); DOI: <https://doi.org/10.1140/epjs/s11734-025-01605-z>
 - 3) A. Shraier, P. Constantin, et al., to be submitted to European Physical Journal A.
- Conference proceedings:
 - 1) A. Mollaebrahimi, P. Constantin, et al., Nuclear Physics A 1057, 123041 (2025); DOI: <https://doi.org/10.1016/j.nuclphysa.2025.123041>.
- Talks at conferences and workshops:
 - 1) P. Constantin: International Symposium on Nuclear Science (ISNS-24), Sofia, Bulgaria, 9-13 September 2024.
 - 2) A. Rotaru: International Symposium on Nuclear Science (ISNS-24), Sofia, Bulgaria, 9-13 September 2024.
 - 3) P. Constantin: Super-FRS Collaboration Meeting, Moerfelden-Walldorf, Germany, 30 October-1 November 2024.
 - 4) P. Constantin: 5th HADO-CSC Workshop, GSI, Darmstadt, Germania, 3-4 September 2025.
 - 5) P. Constantin: Super-FRS Collaboration Meeting, Moerfelden-Walldorf, Germany, 16-19 September 2025.
- Experimental proposals:
 - 1) Proposal G-24-00274 “Next stage of MNT driven neutron-rich isotope studies at the FRS Ion Catcher” by P. Constantin, S. Bagchi, T. Dickel et al., ranked A+ by the G-PAC and scheduled to run in 2027.
- Scientific and technological reports:
 - 1) “Helium Recovery Unit for the LEB CSC” – Design Report GSI Helmholtz Center for Heavy Ion Research GmbH, Darmstadt, Germany.

5. Further group activities (max 1 page)

After the successful proof-of-principle experiment G-22-00117, performed in May 2024, the research program for secondary radioactive ion beams at the FRS-IC facility and tertiary

² 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)

radioactive ion beams at the Super-FRS facility has been established as viable and will be pursued. Consequently, a new experiment has been approved to run in 2027 at the FRS-IC, and the project team has started discussions within the Super-FRS collaboration to plan for the program extension at FAIR.

At the end of 2026, the first stages of two new gamma beam facilities will become operational at ELI-NP. Hence, starting from 2027, early research programs using these beamlines will be developed. The team of the InCellMNT project is currently investigating possible applications of the ion catcher technologies to be deployed with these low intensity gamma beams and, later, with their higher intensity stages.

The increase of the knowledge basis related to secondary radioactive ion beams, which has resulted from the activities of the project, led to the natural growth of the project team, as reflected by the addition of four new team members. The hiring and training of young scientists will remain a core objective of the project.

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

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

The main activity remains the analysis and publication of experimental data acquired in 2024. This activity is very advanced, with one proceedings article published [1], one full article ready for submission [2], and another full article in preparation. The final article targets fully corrected production rates of MNT TLFs, studied as function of several parameters, such as the beam energy and the reaction product mass and charge.

A new activity, which appeared after the approval of the new experiment for 2027, contains a series of tasks for its preparation at the FRS-IC facility: a new degrader system will be designed and installed, a new target type made from a U-Mo alloy will be designed and installed, a new radiation shielding needs to be added around the ion catcher. This new experiment, which will employ the $^{238}\text{U}+^{238}\text{U}$ MNT reaction will finish the initial goals of the project. Specifically, it will measure about 20 new neutron-rich actinide isotopes, as shown in Figure 6.

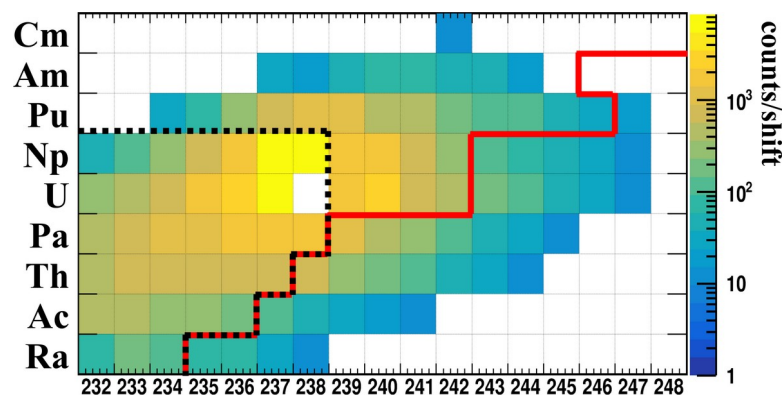


Figure 6. Estimated actinide isotope counts measured in one shift with the MR-TOF-MS, corresponding to ^{238}U at 10^7 ions/s on a $25\ \mu\text{m}$ U target. Full red line shows the current mass limit from NUBASE 2020. Dashed black line shows the production region of U fragmentation.

On the technical side, the completion of the HRU and MCP systems by the end of 2026 will also have a high priority. All implementation tasks are scheduled to be finished by the Summer of next year, leaving the later half of 2026 for testing and commissioning tasks.

Financial Report

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

		lei	
Type of expenditures		Year/ Whole period	
		Value	
		Planned	Realized
1	PERSONNEL EXPENDITURES , from which:	239.948,00	278.512,00
	1.1. wages and similar income, according to the law	234.668,00	272.383,00
	1.2. contributions related to wages and assimilated incomes	5.280,00	6.129,00
2	LOGISTICS EXPENDITURES , from which:	62.070,00	59.479,00
	2.1. capital expenditures	10.070,00	11.511,00
	2.2. stocks expenditures	5.000,00	0,00
	2.3. expenditures on services performed by third parties, including:	47.000,00	47.968,00
3	TRAVEL EXPENDITURES	50.000,00	14.173,37
4	INDIRECT EXPENDITURES – (OVERHEADS) *	119.682,00	119.535,63
TOTAL EXPENDITURES (1+2+3+4)		471.700,00	471.700,00

* Specify the rate (%) and key of distribution (excluding capital expenditures): 35.09% 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.