Call: FAIR-RO 2020 **Project acronym: NAFRO**

Experiment: NUSTAR

Scientific Domain: nuclear physics, nuclear astrophysics

Midterm Summary Document[1]

Year: Nov. 2020 - Jun. 2022

Project Title: Nuclear Astrophysics in FAIR-RO / NAFRO

Project Work Plan (according to the contract)

Stage: I - 2020

Activities: **Integration in FAIR**

I. 1. Integration in FAIR

Stage: II – 2021

Activities: **Experiments at FAIR Phase 0 / Code simulation AB2/ Workshops**

II. 1. Experiments at FAIR Phase 0 / Workshops

II. 2 Code simulation AB2 / Article IMNA

Stage: III - 2022

Activities: **Proposal exp. 16N / Code EoS hot stellar matter**

III. 1. Proposal exp. 16N / Code EoS hot stellar matter

	TOTAL	**2020**	**2021**	**2022***
Allocated budget:	1.246.154,00	138.462,00	553.846,00	553.846,00
Realized budget:	930.044,62	138.462,00	553.846,00	237.736,62

***) Realized value for 2022: 1 January 2022 - 30 June 2022**

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

1. Cover Page

- **Group list (physicists, staff, postdocs, students)**

  The project team was composed by the following members:

  1. Livius TRACHE, Project Director (PD), CS I
  2. Adriana RADUTA, senior researcher, CS I
  3. Florin CARSTOIU, senior researcher, CS I
  4. Alexandra SPIRIDON, PhD, Research Scientist
  5. Alexandra-Ionela CHILUG, PhD student, Research Assistant
  6. Ionut-Catalin STEFANESCU, PhD student, Research Assistant
  7. Dana TUDOR, PhD student, Research Assistant
  8. Iuliana STANCIU, PhD student, Research Assistant
  9. Andreea SUVAILA, economist

- **Specific scientific focus of group**

The focus of the Nuclear Astrophysics Group (NAG) at the Department of Nuclear Physics (DFN) from IFIN-HH is **nuclear physics for astrophysics**. This is a group of experimentalists who are using direct measurements at the local IFIN-HH's accelerators (mostly the 3 MV tandetron) and **indirect methods with radioactive ion beams (RIB) for nuclear astrophysics at FAIR** or **other international RIB** facilities**.** These latter activities are mostly funded through this project, while their work with direct methods is being supported from different grant(s). The group is directly lead by the Project Director (PD). In addition, theory work on the **Equation of State of nuclear matter in dense star properties and evolution** is done under the leadership of **prof. Adriana Raduta** and on **ion-ion potentials** with **dr. Florin Carstoiu** of the Department of Theoretical Physics (DFT)**.** He has retired since Jan 2022.

- **Summary of accomplishments during the reporting period**

The period on which we report here includes the periods for which we submitted annual 2020 and 2021 Intermediary Reports. Therefore, this report, by necessity, includes activities and even wordings we reported on, we just add activities on December 2021 and the first half of 2022. Work was perturbed by the on-going pandemia crisis induced by the corona virus. While these conditions affected the initial timing plans very much, they did not affect substantially the results. The latter part, July 2021 to present was, however, closer to normal. We focused on group's integration in FAIR and participation on joint activities at GSI/FAIR, including experiments of Phase 0. We participated actively in the scientific life of the R3B and Super FRS Experiment Collaborations, part of NUSTAR, participated on-site at GSI to the setup and to the runs of two experiments of the Phase 0 spring 2022 campaign (S522 and S509).

One important part of the time and work was dedicated to finalizing of the PhD thesis of the four students of the group. They plan to present them to the respective committees in the early or mid-fall 2022, and I have strong reasons to believe that that will happen.

The workshops planned were affected, mostly in timing and format, but they were successfully, with good international participation and echoes

2. Scientific accomplishments

Advances on experimental work

In the whole period we focused on our integration in FAIR or continued it. Namely we focused on contacting the groups that are working on the specific topics we are interested in, and we could contribute to, as included in the proposal. With emphasis on informing ourselves about the status of the experiments scheduled to take place in the next beamtime period of FAIR Phase 0, in 2021, 2022 and beyond. We participate in the **R3B** and **Super-FRS Experiment Collaboration (SEC)** of **NUSTAR**.

No travel to FAIR was scheduled or possible in the first half of the year 2021, the way to contact and get up to date was through the participation at the extended on-line meetings scheduled in this period. These were the normal periodic meetings of NUSTAR, SEC or R3B, or meetings between our group and smaller groups working at FAIR. In end-September, three members of the group (the PD si 2 students) have participated in-person at the SEC meeting in Waldorf-Moerfelden, Darmstadt (Sep. 22-24) and visited GSI and TU Darmstadt. This allowed us to improve our contacts with the Super-FRS, R3B people and their physics. One of the results is that one member of the group, **dr. Alexandra Spiridon**, was at GSI-FAIR for a 5-week period (Nov. 2 – Dec. 6) with two main tasks:

- Contact with the SEC group that carried out the Phase 0 experiment S459+, to result in taking part in the analysis of most of the data from that experiment (about 95% of data, according to dr. I. Mukha, its leader).
- Participation at a test experiment at FA Julich for detectors, electronics, DAQ and software to be used by SEC groups.

We were also registered to participate in the R3B Collaboration meeting on Dec. 13-17, 2021. At the Dec. 17th R3B Collaboration Board meeting, the PD was scheduled to present our group's proposal. Following that, the R3B Collaboration Board voted to include our group formally into the collaboration and I signed the CA. Later, the PD was elected in the Science Board of R3B and activated there since.

In the first part of 2022 our involvement at GSI/FAIR was more direct: two students, Alexandra Stefanescu and Ionut Stefanescu, spent two months each at GSI, in two tranches:

(i) **February 13th - March 30th, 2022:** involved in the team which prepared an array of 8 silicon strip detectors (FOOT) and their associated electronics, mounted around the target, for future experiments of R3B and SEC. The silicon detector system was tested in-beam during the test experiment at GSI (14th-19th March), part of the S522 research project, with ^{12}C beam accelerated at 1.25 AGeV. The motivation to use these silicon detectors was to tag the interest reaction channel (p,2p) by tracking the protons emitted at angles larger than 20^0 and the induced fragments emitted at forward angles. During the last week of the trip, they attended an experiment at IKP - Julich, to test on the COSY beam line components of FOOT and ALPIDE silicon pixel detectors. Supported by this project.

(ii) **May 8th - June 5th, 2022:** joined the Phase 0 experiments S522 ("First characterization of Short-Range Correlations in exotic nuclei at R3B" - spokesperson A. Corsi) and S509 ("Study of drip-line phenomena in neutron-rich nuclei" - spokesperson O. Sorlin). AS has become responsible mostly for the FOOT detectors group which prepared 12 FOOT silicon strip sensors and had shifts during these two experiments to monitor and do online analysis for the FOOT detectors signals, while IS was part of the FRS team working to provide the radioactive beams for these experiments. The financing of this period was provided by the STRONG 2020 program.

It is to be noted that the students' education and training during the previous term of FAIR-RO program under the NAIRIB project and their experience from work home and at RIKEN, allowed them an easy and fast integration in the GSI/FAIR groups. As a result of these activities in the FOOT silicon detectors group, the students or the group were asked to be collaborators on several R3B and SEC proposals submitted in June 2022 to the G-PAC.

Activities in connection with future participation to FAIR activities were also pursued at home:

- Two of the PhD students continued the analysis of their respective thesis data: on the ^{9}C nuclear and Coulomb dissociation at intermediate energies - Sect. 4.1 of the proposal - (Alexandra Chilug-Stefanescu, experiment NP1412-SAMURAI29R1 at RIKEN) and βp-decay of ^{27}P – Sect. 4.2 - (Ionut Stefanescu, Texas A&M University experiment). These analyses were also slowed down considerably by the sanitary crisis and are planned for completion the fall of 2022. A paper was submitted to Eur. Phys. J. A, dealing with a Si-tracker array similar to FOOT.
- Simulations of our ASTROBOX2 detector. This detector is dedicated to measure beta-delayed proton-decay (βp), with focus on very small proton energies E_p=100 – 600 keV, corresponding to nuclear astrophysics relevant resonances in radiative proton capture reactions. The simulations are useful to describe well the detector performances in future experiments, in particular of its efficiency as function of the energy of emitted protons. Figure 1 illustrates some of simulations' results. In the discussions with the SEC group, we and our GSI/FAIR colleagues advanced the idea that the detector can be used as a complementary device in the system EXPERT, an idea that we will pursue in the coming years.

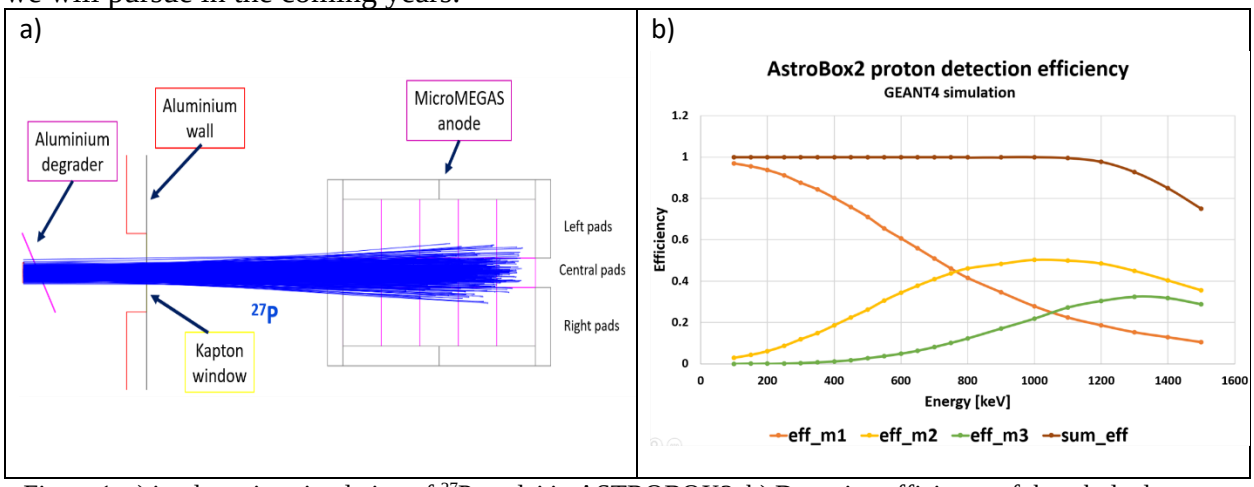

Figure 1. a) implantation simulation of ^{27}P nuclei in ASTROBOX2. b) Detection efficiency of the whole detector as function of emitted proton energy (orange, yellow and green are for 1, 2 or 3 pads responding, top brown is the sum).

We have explored further the idea we advanced to study the **beta-delayed alpha-decay of ^{16}N** as a complement to the GSI studies aiming at the reaction ^{12}C(α,γ)^{16}O, one very important in nuclear astrophysics. While this is not a new idea, our ASTROBOX2 detector advances very much the experimental possibilities, in terms of resolution and sensitivity. We made a proposal to make this study in collaboration with the group of prof. XD Tang (who has past work at Argonne NL on the topic) at Texas A&M or at IMP Lanzhou. The idea is studied by the partners: a formal internal grant application was in parallel submitted by the Chinese collaborators; TAMU does not have a formal PAC, we approached the MARS group members. The latter place seems to offer best conditions as they have ^{16}N beam of 1-2*10^{6} pps and a good ASTROBOX2 detector. For NAG we foresee a manpower problem that we may solve through the collaboration with IMP.

Advances on theory

The composition and structural properties of cold, mature neutron stars in weak β-equilibrium, depend on a one-parameter equation of state (EoS) that relates the pressure to the energy density. On the contrary, dynamics of core-collapse supernovae, evolution of proto-neutron stars, formation of stellar black holes, and the post-merger phase of binary neutron star mergers require an EoS depending on three thermodynamic parameters, typically chosen as temperature T, baryon number density n_B, and electron fraction Y_e. These need to cover wide domains: 10^{-14} fm$^{-3} \leq n_B \leq 1.5$ fm^{-3}, $0 \leq Y_e = n_e/n_B \leq 0.6$ and 0

≤ T ≤ 100 MeV. Since a long time, numerous numerical studies of these different phenomena show a considerable sensitivity to the EoS.

In the last decades the EoS of cold neutron stars has been intensively studied and constrained by experimental nuclear physics data, astrophysical data from radio/X-ray pulsars, gravitational wave events, and ab initio calculations of (neutron) matter. The different data are complementary in the sense that the conditions of each measurement imply that constraints on the EoS can be obtained within a particular density and isospin asymmetry domain. In particular, nuclear experiments are naturally performed for matter with densities below saturation density $n_{sat} \approx 0.16$ fm $^{-3} \approx 2 \cdot 10^{14}$ g/cm ^{3} and for a nearly equal number of protons and neutrons, and ab initio calculations are the most reliable for low density ($<1 - 2\ n_{sat}$) pure neutron matter. Recent developments in nuclear physics and astrophysics allowed to considerably narrow down the parameter space of cold β-equilibrated neutron stars, symmetric nuclear matter and pure neutron matter. The situation is more complicated for the finite-temperature EoS potentially out of weak equilibrium.

The main motivation of this work is to try to better understand the finite temperature EoS. To this aim we plan to build several 3D general purpose EoS tables, accounting for various exotic particle degrees of freedom as hyperons and nucleonic resonances. The theoretical framework we adopt is the covariant density functional theory. The key ingredient of the models in this category is the Lagrangean density. Interaction among particles is mediated by the exchange of several scalar and vector mesons. To cover a wide range of possibilities we shall account for models with non-linear couplings as well as models with density-dependent coupling constants. For the nucleonic sector we shall use parametrizations in the literature, where the coupling constants have been tuned such as for a series of nuclear properties to be described. Coupling constants of exotic particles with the mesonic fields are chosen, as customarily in the literature, such as to agree with the values of potential well depths derived from experimental data or based on symmetry arguments. Matter composition and energetics for any thermodynamic set in the wide 3D space is determined by solving the corresponding equations, including those corresponding to chemical equilibrium between the species. The necessity to cover a grid with typically one million points, with extremely different matter composition and structure, makes this task a challenging one. Despite the CPU costs one should make sure that convergence is reached in an overwhelming fraction of cases. The code we have developed employs standard multiroot solvers as well as solvers written by us for this particular purpose. Its behavior is good in terms of both number of steps for convergence and success rate. We plan to exploit is extensively and make all the built EoS publicly available for the astrophysics community. We expect our efforts to contribute both to a better understanding of astrophysical environments where hot baryonic matter is populated and better constraints on the nuclear EoS, including the exotic channels. This work was done in the group of prof. Adriana Raduta, with whom we closely cooperate. They wrote a code, that produced results. These results were presented at several conferences, in-person or online and one publication: A.R. Raduta, F. Nacu and M. Oertel, Eur. Phys. J. A, (2021)57:329. However, those activities were financed by a PCE grant obtained in 2021 by prof. Raduta.

A typescript on the ion-ion potential topic was prepared by dr. F. Carstoiu “Rainbow-Regge ripples competition in α-scattering” (but not submitted so far). We are not reporting on it here.
Beginning Jan. 1, 2022, dr. Carstoiu retired.
The NAG group was included in the JINA prepared white paper about the future of nuclear physics for astrophysics, which was submitted and will be published in Journal of Physics G of IOP.

3. Group members (table):

First Name, Last Name	Academic Degree	Realized FTE 2020	Realized FTE 2021	Realized FTE 2022 (30 June)
Livius-Marian TRACHE	SR I	0,10	0,68	0,10
Adriana Rodica RADUTA	SR I	0,07	0,08	0,00
Florin CARSTOIU	SR I	0,00	0,04	0,00
Alexandra Elena SPIRIDON	RS	0,01	0,00	0,00
Alexandra Stefanescu	RA	0,10	0,41	0,12
Ionut Stefanescu	RA	0,10	0,41	0,13
Dana STATE	RA	0,00	0,00	0,11
Iuliana Madalina STANCIU	RA	0,00	0,00	0,21
Andreea SUVAILA	Econ	0,00	0,00	0,00

4. Deliverables in the last year related to the project:

- List of papers (journal or conference proceedings)
  - A. Stefanescu, V. Panin, L. Trache … et al., "Silicon tracker array for RIB experiments at SAMURAI", Submitted to Eur. Phys. J. A
  - H. Schatz, …, A. Spiridon, L. Trache et al., "Horizons: Nuclear Astrophysics in the 2020s and Beyond", accepted to J. Phys. G, 2022
  - F. Carstoiu, M. Lassaut, L. Trache "Rainbow-Regge ripples competition in α-scattering", prepared for Rom. J. Phys., to be submitted
- List of talks of group members (title, conference or meeting, date);
  - Livius Trache - "Carpathian Summer Schools of Physics – short presentation and INVITATION to CSSP20 in Aug. 18-27, 2021", SNAQ5 (online), June 9, 2021 (https://events.hifis.net/event/113/)
  - Adriana R. Raduta – "Nuclear equation of state and physics of compact stars", (online), SNAQ5, June 9, 2021.
  - Alexandra Spiridon – "Study of ion-ion fusion mechanisms at sub-barrier energies for nuclear astrophysics", invited talk, ECT* 2021 KRINA (online), June 22-23, 2021.
  - Adriana R Raduta - "Nuclear EoS and neutron stars", invited lecture, CSSP20, Sinaia, Aug 18-27, 2021
  - Alexandra Spiridon - "Ion-ion fusion reactions at sub-barrier energies", invited lecture, CSSP20, Sinaia, Aug 18-27, 2021
  - Alexandra Stefanescu - "Breakup of ^{9}C ", oral communication CSSP20
  - Iuliana Stanciu – "Search for Supernova R-process actinides in geological reservoirs", oral communication", CSSP20
  - Ionut Stefanescu – "βp-decay of ^{27}P", oral communication, CSSP20
  - Livius Trache - "Nuclear astrophysics studies at IFIN-HH", European Summer School of Experimental Nuclear Astrophysics 2022, Catania, June 12-19, 2022
  - Iuliana Stanciu – "Accelerator Mass Spectrometry of Plutonium: beyond isotopic ratios", 14th European Conference on Accelerators in Applied Research and Technology, Sibiu, July 2022
- Other deliverables (TDR, patents, books etc.). http://proiecte.nipne.ro/ifa-fair/4-projects.html
  https://www.nipne.ro/proiecte/pn3/29-proiecte.html
  https://www.nipne.ro/events/conferences/cssp20/
  https://indico.nipne.ro/event/141/attachments/79/155/Program_CSSP20%20-%20last.pdf
  https://www.ectstar.eu/workshops/key-reactions-in-nuclear-astrophysics/

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

Workshops and outreach events

Several scientific and outreach events were initially proposed for 2021, under the reserve that sanitary conditions will permit. Only two of them, the most important scientifically, could be carried out:

- **ECT* workshop "Key Reactions in Nuclear Astrophysics KRINA",** proposed and accepted by the ECT* Scientific Board for June 2020, was postponed for same week in 2021, but could not take place with in-person presence in Trento, Italy. It was replaced by a two-day online event on June 22-23, 2021, and the workshop with hybrid format **was rescheduled for December 11-16, 2022**. It is organized by the PD In collaboration with A. Tumino (LNS Catania, chair), J. Jose (UPC Barcelona), C. Bertulani (TAMUC) and R. Diehl (MPIEP, Muenchen).
- The **29th edition of the Carpathian Summer School of Physics 2020** "Exotic Nuclei and Nuclear/Particle Astrophysics (VIII). Physics with small accelerators", was postponed for 2021 and took place successfully on Aug. 18-27, 2021, in Sinaia. That appeared to have been an excellent and short window of opportunity, as the sanitary situation in Romania worsened again from the end of September 2021. We base the appreciation "successfully" on the large number of participants (81 in total, compared with 20-30 we assumed when launched it in June) and on the opinions of the participants. Report attached.
- The **SNAQs** (School on Nuclear Astrophysics Questions), organized by a group formed under the European project ChETEC-INFRA, of which we are part. These are online monthly events, beginning in March 2020, organized and moderated by the organizers of the European nuclear Astrophysics schools. 13 editions were held so far. PD has organized 2 specific editions (and will organize one more by the end of 2022)

The 2021 edition of the Summer School for Physics Olympics (5 editions carried before) could not be organized due to the pandemia.

6. Financial Report (budget usage) for the reporting period (see the Annex).

The funds of the project were largely used as approved, mostly for the salaries of the students covered. In 2021, half of the funds proposed for travel expenses could not be used and were transformed into Logistics, namely for the acquisition of electronic modules needed for the local DAQ of the group.
For 2022 we are on track of using the funds as planned.
The details are in the **Annex** attached.
It is to be noted that the funds needed by the NAG group were supplemented by other sources, including the "Program Nucleu" of DFN and a grant PCE obtained later in 2021 by prof. A Raduta.

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

In the coming year and a half, NAG will concentrate on three directions related to NAFRO:

- The PhD theses of the four students will be finalized and defended.
- Participation to the activities of the R3B and SEC collaborations at GSI/FAIR, including the preparation and running of the new experiments submitted to the G-PAC session of 2022.
- The organization of outreach and training events.

PhD theses of NAG students

All four students of the group are in the final stage of preparing and defending their PhD theses. All are on nuclear astrophysics subjects and three of them are directly connected with this project. The fourth,

that **of Dana Tudor,** is based on direct measurements we did at IFIN-HH in previous years. The results were published in 2020 (one **Phys. Lett. B** and one **NIM A**), Dana returned from her 2 years of maternity leave and she is advancing with her write-up. **Iuliana Stanciu** has finished her stage as PhD student at TUM in the group of the late prof. Shawn Bishop and this month submitted a first draft of the thesis to me and her new TUM advisor. If accepted, she'll defend by the end of August.
Alexandra Stefanescu and **Ionut Stefanescu** spent one year (Nov. 2019 – Nov. 2020) as IPA fellows at the Nishina Center of RIKEN, Wako, Japan. Their stay there was very much affected by the covid pandemic, which permitted lower contacts with the local groups (lower than I expected, for sure). However, their analyses on the data they were responsible for, proceeded. A paper, A. Stefanescu et al. was submitted for publication to Eur. Phys. J. A.

GSI/FAIR Collaborations
At this point NAG's members are, explicitly or implicitly, part of several experiment proposals for the 2022 G-PAC session. R3B decided to name only the spokespersons on the proposals, while SEC included all people that count on as direct participants. NAG members are part of 5 SEC proposals. We will participate directly to the activities implied by the experiments approved and scheduled in 2023, with the manpower available at the time and within the financial possibilities.

Outreach and training events
At this point we plan the following events, organized under direct participation

- the SNAQ in Sep-Dec. 2022,
- the workshop "Key Reactions in Nuclear Astrophysics KRINA" at ECT* Trento, Italy (in-person finally – and hopefully), scheduled for Dec. 11-16, 2022
- the 30^{th} edition of the Carpathian Summer School of Physics on July 2-15, 2023. That will be the 10^{th} edition on Nuclear Astrophysics topics (and probably the last). We have secured already the seed financing by the European project ChETEC-INFRA and by an internal IFIN-HH program.
- One training school at IFIN-HH in 2023, to be organized under EURO-LABS European project.