Report **NAFRO2 2025**

- **Specific scientific focus of group**

In the reporting period, Jan – Nov. 2025, the focus of the Nuclear Astrophysics Group (NAG) from IFIN-HH has remained **nuclear physics for astrophysics**, as per the proposal. We combined the **experimental work** at home and in GSI **at FAIR Phase 0 of the R3B and Super-FRS** experiments with the work of dr. **Dan Cozma, a theorist with activities in the field of transport models for the study of nuclear matter in extreme conditions** of charge symmetry, in particular. In addition, we co-organized the **KRINA25** (Key Reactions in Nuclear Astrophysics 2025) at ECT* Trento and have organized the **CSSP25** (Carpathian Summer School of Physics 2025) in Sinaia.

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

In summary, during 2025 the group maintained its work on the proposed thematics at GSI/FAIR, within IFIN-HH, and in international contexts. The experimentalists participated in Phase 0 experiments, including preparations and beamtime, as much as our diminishing work force and finances allowed, the theory branch was working on TMEP, and all worked on the organization of two important international scientific events. We transferred our ASTROBOX2E detector to GSI, together with our postdoc I. Stefanescu, who spent the year working on its installation, its simulation and its possible insertion in the setup of the S-FRS collaboration.

The impact of the momentum dependence of effective interactions on equilibrium multiplicities of nucleon, $\Delta(1232)$ isobars and pions in infinite uniform nuclear matter (both isospin symmetric and asymmetric) is studied using three different transport models (RVUU, AMD+sJAM and dcQMD) as part of the Transport Model Evaluation Project (TMEP). The importance of including threshold effects in the collision integral and choosing similar parametrization of the interaction over the entire range of probed momenta is highlighted for convergent predictions. To facilitate comparison among transport models, Pauli blocking of final states in two-body collisions and the Coulomb interaction are switched off. Predictions for equilibrium quantities of each transport model are compared to exact results derived using thermal models employing the same interactions. This allows to pinpoint the source of residual differences among transport model predictions that persist as result of different parametrization for the momentum dependent interaction used in each code. Finally, model performance for the case of heavy-ion simulations is assessed by studying the early time evolution towards equilibrium, since in-medium cross-sections, crucial for particle production, only impact the relaxation time of the system [1].

We have continued to work with collaborators at other RIB facilities (RIBF at RIKEN, Cyclotron Institute at Texas A&M University, LNS Catania, IMP Lanzhou) on experiments, data analysis, scientific events and publications.

KRINA25 (Key Reactions in Nuclear Astrophysics 2025) at ECT* Trento and **CSSP25** (Carpathian Summer School of Physics 2025) in Sinaia were two scientific events that we organized. Our considerable efforts lead to their success, according to the participants and the community. We started the preparation for the EURO-LABS school BTS26 on May 11-23, 2026, as a new hands-on training event at IFIN-HH and NAG is leading.

It is important to note the changes in our group, as its younger parts went ahead in their careers, all in the right direction: dr. Iuliana Stanciu went to work at a new AMS facility in UK; Wajahat Syed, the master student from India was accepted in the PhD program of the prestigious NSCLA, Michigan State University, USA; Andrei Opincă graduated (BS) from the University of Bucharest and was accepted to a master program at the Technische Universität Darmstadt, Germany, with a DAAD fellowship; very recently dr. Ionut Stefanescu got a two-year post-doc position at TUDa/FAIR and leaves on Nov. 30, 2025.

2. Scientific accomplishments

Experiments.

II.1 We have continued our involvement in FAIR Phase 0 experiments and experiment preparations at GSI. In addition to participating in the beamtime campaigns of 2024 and 2025 we participated in the preparation of the 2025 and 2026 beam campaigns at GSI and in the preparation of new proposals for the G-PAC session. In September 2024 we transferred the ASTROBOX2E detector to GSI and delegated Dr. IC Stefanescu for most of the year to GSI to complete it and implement it in a new environment. Participation in experiments was limited by our resources, both human and financial. However, we were able to finance the stay and work at GSI of our postdoc, dr. IC Stefanescu. This resulted in his involvement in both in-beam shifts and earlier stages such as setups and tests. In addition, ICS has represented the group or the institute to all local (GSI/FAIR) workshops or collaboration meetings to which we could not be present: Super-FRS Experiment Collaboration Meeting in Waldorf, Sept. 2025; NUSTAR week, Sept-Oct 2025...

While disappointed that our G-PAC 46 proposal "β-delayed proton decay of proton rich nuclei as a tool to study (p,γ) reactions in extreme stellar environments", submitted at the end of 2024 and presented in January 2025 on behalf of NAG, with ICS as spokesperson, was not granted beamtime but remained a LoI, that put our device ASTROBOX2E on the map of NUSTAR collaboration, such that the device may get to be tested on available parasitic beam(s). As a result of the overall experience, he was offered a two-year postdoctoral position at GSI and TU Darmstadt. He will begin on Dec. 1st this year. While this diminishes NAG's available workforce, I consider this appointment as a success and a recognition of my group's ability to grow and train good quality scientists. This was and is one of our main purposes. A few lines above I included the list of those that promoted from the group, this year alone: two postdocs to UK and Germany, one PhD student to USA and one master student to Germany.

NAG or some members are part of proposals prepared at the R3B and Super-FRS collaborations for G-PAC 2022 and G-PAC 46. Of those new proposals 4 were approved. We participated in those experiments that were run already:

G-22-00115 – approved, run in Feb-Mar 2025

G-22-00111 - approved, run in May 2025

G-22-00122 - approved, run in Mar 2025

The ASY-EOS-II experiment at GSI/FAIR: studying the EoS (Equation-of-State) of neutron rich matter at high baryon densities, Arnaud Le Fevre, GSI

G-24-00249 - approved A, run in May- June 2025

Unveiling the structure of neutron-rich Z=9 isotopes: the case of 25F, Valerii Panin, GSI

While participating in setup, test and beam runs, we are not responsible for data analysis.

NAG continued to work at home on nuclear astrophysics inspired experiments. Many efforts were dedicated to two subjects: (i) the preparation, characterization and use of targets for nuclear astrophysics experiments and (ii) the study on ion-ion fusion mechanism(s) at sub-Coulomb energies. Both subjects were worked on for a few years, formally in large international collaboration, but the main burden was on our shoulders, as the experiments were carried on at the 3 MV tandetron of our institute. Three beamtime campaigns, led by dr. Alexandra Spiridon, were carried out together with colleagues from the LNS Catania, Italy and IMP Lanzhou, China. The participation of our guests in experiments was partly financed by the European project ChETEC-INFRA, to which we were part in the last 4.5 years. One article was published on the work on the first topic (i) and another one is being prepared for submission on the second (ii).

NAG has remained also connected to other facilities where topics of this project are active, however, while we participated in experiments in 2024 and in the preparation of new campaigns, we did not participate in-person this year. PD is a member of the SAMURAI Collaboration Board at RIBF of RIKEN, Wako, Japan and has participated and participate on-line to its works and meetings.

II. 2 Simulations. A GEANT4 environment was setup for the simulation of beta-delayed proton (βp) and beta-delayed alpha ($\beta\alpha$) decay measurements in ASTROBOX2E. The appropriate geometry was implemented in the code, then the radioactive beam was implanted in the middle of the P10 gas filled detector, followed by its decay. The decay consists of the simultaneous emission of a positron and a proton. Both give signals in the detector, a very small one from the positron (continuous, 1-3 keV), the most important from protons of specific energies (100 keV and up). The ionization charges are collected on anode. Geometrical distribution on the anode and energy spectra are obtained. Case in point: ^{31}Cl, for which ICS analysed data we obtained earlier at the Cyclotron Institute, Texas A&M University.

A comment has a place here. We envisaged for some time to obtain indirect method data on the radiative alpha-capture on 12C at nuclear astrophysical relevant energies. However, this proves somewhat elusive: the Coulomb Dissociation of 16O at the R3B GSI did not produce significant results and currently the team is dismantled. The alternative: use of beta-delayed alpha-decay of 16N using ASROBOX2E and the collaboration with specialists from IMP Lanzhou, China, looks difficult now: GSI does not produce an appropriate 16N beam and politics prevents us going to the Cyclotron Institute, Texas A&M University. That may not be that problematic, given that this reaction is sought for over 60 years!

II. 3 Theory. The Transport Model Evaluation Project (TMEP) aims at comparing transport model predictions under controlled conditions with the final goal of understanding and alleviating model uncertainties. To achieve that each ingredient has to be tested separately by simulating well-chosen systems for which exact results are available at least for some limit case. Up to now the elastic and inelastic components of the collision term have been studied in the cascade mode (interaction switched off) testing the robustness of Pauli blocking [2] and detailed balance [3] implementations respectively. This was followed by the study of pion production in heavy-ion collisions close to threshold using a momentum independent interaction [4]. However, using a momentum dependent interaction is mandatory for a realistic description. Given the strong dependence of particle emission close to threshold on the strength of the momentum dependence of the interaction, in one-to-one correspondence with values of effective masses of particles involved, the variety of employed parametrizations and approaches available in the literature it is best to first study the model dependence of such an ingredient for simpler systems. Uniform nuclear matter falls in that category, providing the additional opportunity of comparing to exact results for equilibrium quantities obtained using a simple thermal model.

To that end the following systems have been simulated: symmetric and asymmetric (δ=0.2) nuclear matter at saturation density. The initial state is made up of neutrons and protons with initial momentum distributions given by the relativistic Boltzmann distribution with temperature T=60 MeV. In each case 1280 nucleons contained in a cubic box with side L=20 fm and periodic boundary conditions are considered. The system's evolution toward equilibrium is determined up to 150 fm/c with a required time-step not larger than 0.5 fm/c. Besides elastic nucleon-nucleon collisions, the following inelastic channels have also been considered: $NN \leftrightarrow N\Delta$ and $\Delta \leftrightarrow N\pi$. Cases with pion production switched on or off have been simulated, similarly to a previous TMEP study[2], dubbed phases. To better understand the impact of momentum dependent interactions several cases have been simulated for each phase: cascade with vacuum masses, cascade with effective masses, momentum-dependent interaction (no threshold effects) and full with momentum-dependent interaction (threshold effects included). The first one represents a consistency check with Ref. [2], the second provides an useful approximation to the fourth (most realistic one), while the third resembles an often employed scenario in the past publications on this topic leading to infamous puzzles (e.g. very soft density dependence of symmetry energy, violation of energy conservation). Threshold effects represent the impact of in-medium potential on kinematics of elementary collisions, leading to modifications of incoming flux and final-state phase space and thus manifest as in-medium modifications of elementary cross-sections. The following transport models have been used for simulations: dcQMD [5], RVUU [6] and AMD+sJAM [7], the authors of each of these codes providing simulation results and detailed explanations.

The first important conclusion is drawn by studying isospin symmetric nuclear matter with only $NN \leftrightarrow N\Delta$ inelastic channel switched on (no pion production) for the full case mentioned above. Setting Δ(1232) potential equal to the nucleon potential represents a common choice in literature. It turned out that for relativistic models this holds true only at p=0 GeV/c. Furthermore, the Δ(1232) potential exhibits a dependence on resonance's mass due to the definition of the potential in this case. Consequently, a convergence of model predictions for equilibrium Δ-isobar multiplicities requires a fine-tuning of the momentum dependence of both nucleon and Δ potentials over the entire range of probed momenta. Fixing only the value of the effective was found insufficient, a second parameter, related to the magnitude of potentials for large momenta, had to be tuned to achieve convergence at 5% level among the three transport models. A good agreement with thermal model predictions was also obtained. Equilibrium Δ-isobar multiplicities drop by a factor close to three when threshold effects are switched off, leading to an equally large disagreement with thermal model predictions and thermodynamical inconsistencies. Similar conclusions hold true for the case of isospin-symmetric matter and the isovector component of nucleon and Δ-isobar potentials.

Simulations including also pion degrees of freedom present similar features. For these cases also the time-step has been varied allowing an extrapolation to dt=0.0 fm/c (AMD+sJAM is time-step independent). A comparison of equilibrium multiplicities for the Δ-baryon and pions in this limit to exact thermal model results reveals discrepancies of at most 5%. No clear trends could be identified. A given model may describe Δ-baryon multiplicities at 1-2% level but show deviations for pion multiplicities of 5%. The most likely explanation is that of higher order correlations induced by choices in the order of how elementary reactions are implemented in the code, similar to cascade calculations [2]. A comparison of Δ-baryon mass distribution at equilibrium to exact thermal model results has been performed. RVUU and AMD+sJAM show good agreement, while dcQMD shows non-negligible deviations (up to 20%) for invariant masses below pole mass. The origin of this discrepancy is at the moment no clear. Similarly to multiplicities, momentum distributions of Δ-baryons and pions agree well with thermal model predictions and among each model.

[1] M.D.Cozma et al. (TMEP Collaboration), in preparation;
[2] Y.X. Zhang et al., Phys. Rev. C 97, 034625 (2018);
[3] A. Ono et al. (TMEP Collaboration), Phys. Rev. C 100, 044617 (2019);
[4] J. Xu et al., Phys. Rev. C 109, 044609 (2024);
[5] M.D. Cozma, M.B. Tsang, Eur. J. Phys. A 57, 309 (2021);
[6] T. Song, C.M. Ko, Phys. Rev. C 91, 014901, (2015);
[7] N. Ikeno and A. Ono, Phys. Rev. C 108, 044601 (2023).

II. 4 Workshops. Our group in Bucharest is already well known in Europe and in the world for organizing international scientific events. This year, **KRINA25** (Key Reactions in Nuclear Astrophysics 2025; https://indico.ectstar.eu/event/228/) at ECT* Trento, Italy and **CSSP25** (Carpathian Summer School of Physics June 22 – July 3, 2025; https://cssp25.nipne.ro/ and also https://indico.nipne.ro/event/382/overview) in Sinaia were two scientific events that we organized. Our considerable efforts lead to their success, according to the participants and the community. In February 2025, the PD of this project was one of the organizers of the ECT* workshop together with profs. Aurora Tumino (LNS Catania), chair, Carlos Bertulani (East Texas A&M Univ., Commerce), Jordi Jose (UPC Barcelona) and Roland Diehl (Max Planck Inst, Munich). This was a well-attended one week event, in the spirit of ECT* Trento, reuniting scientists from the world interested in the identification of the most important nuclear reactions for nuclear astrophysics, including discussions on direct and indirect methods and the most recent results. NAG was also present with an invited talk by dr. Alexandra Spiridon on ion-ion fusion reactions at sub-Coulomb energies. CSSP25 was the 10th edition of IFIN-HH's traditional biennial schools, and it was organized again in Sinaia, June 22 – July 3, 2025. Virtually all members of this project worked on organizing it, co-chaired by the two senior members. The event had 82 participants and featured 48 invited lectures and 20 student contributions that are posted on the website: https://indico.ectstar.eu/event/228/timetable/#all. The event was supported by participants' institutions, by EURO-LABS WP5.4 Training, and by sponsors from economy. A more detailed report was presented after the event and is annexed here.

We started the preparation for the EURO-LABS Basic Training School 2026 (BTS26) on May 11-23, 2026, as a new hands-on training event at IFIN-HH, and NAG is leading. The Organizing Committee was selected (A. Spiridon – chair), the approvals from IFIN-HH Management and Scientific Council were obtained, and the first circular is being distributed. We'll select 24 students, and the European project EURO-LABS supports the costs.