Project: PNII-ID-PCE-2012-4-0299

Project title: "Nuclear astrophysics studies at IFIN-HH"

Intermediate report December 2014

1. Introduction

This is an intermediate report for the project identified above, in Dec. 2014, after 14 month since the beginning of its financing. The project was submitted in April 2012, announced on Nov. 7, 2012 as evaluated with 98 out of 100 points, but its financing started only on Sept 2, 2013 for a reduced duration of 27 months, not 36 as proposed. It has the internal IFIN-HH nr. PNII 27/2013 and some documents may identify it with this number. Due to a late start and financial truncation, some of the objectives will obviously not be as stated in the original proposal. Moreover, after only 3 months of regular financing in 2013, the funds for the project were cut to about 55% of those scheduled for 2014 and a 12 months extension into 2016.. This lead the Project Director (PD) (or Principal Investigator - PI), to a reassessment of program's objectives and in particular of the use of funds. Funds in this project had to be, at points, complemented with funds from other projects. These are clearly shown where the case, and in the financial documents.

2. General report

In this report I will start from part *C. Project description* from the proposal of April 2012 [1] and use the convention that those parts are always in *italics*, to distinguish them from the rest.

The project had two motivations, as declared in part *C1. Introduction to project's problematic:*

- *the intent of the project director to return to Romania after a 19 years stay and work in the United States.*
- *to start … a group working* in nuclear astrophysics *and the present proposal is to establish an initial funding for exploratory research in this area. This is the second, the scientific motivation of this proposal.*

Both goals were largely fulfilled at this point, see the rest of the report for argumentation, with considerable work remaining to consolidate them.

Best approach for this report is to start from the objectives, as stated in Sec. C2 of the proposal. I add numbers to each objective (not present in the original) to help referring to each one later.

C2. Objectives

The concrete objectives of the proposal are:

- **C2.1** *Start a research group in the Department of Nuclear Physics (DFN) of IFIN-HH. That will start with the return of the project director. Search for a suitable candidate for a second permanent position in the group, at CS3 or CS2 level. Search will focus on existing IFIN personnel. Attract two graduate students in the group in 2013 and after.*

- **C2.2** *Start work on the physics of the project. Collaboration with dr. F. Carstoiu of DFT who will be involved 15% of his time in this project will continue on the subject of theory of breakup reactions at intermediate energies. Of prime and immediate concern will be the calculations for the experiments at the RIBF of RIKEN, Japan, scheduled for 2013.*
- **C2.3** *Continue work on projects started earlier while at my TAMU position. Of prime importance will be the THM experiments with the group from Catania. The continuation of the* $^{16}O+^{12}C$ *experiment started by the Dec. 2010 experiment at the IFIH tandem accelerator. Second, move to IFIN the experiment NiCAR approved by the LNS Catania PAC in 2011, in case the Sicilian accelerator will not work. For these to happen a new, improved goniometric system to measure angles in the existing reaction chamber with better accuracy will be developed.*
- **C2.4** *Will complete the current collaboration with the CEA Saclay and CERN groups for the design and construction of a new version of the AstroBox detector built while at TAMU. The new detector will have a better beam efficiency and a better energy resolution for the low energy protons from β-delayed proton emission. Experiments will be proposed at TAMU to test the detector in 2013. After the tests of 2013, proposals will be made to use it at CERN's HIE-ISOLDE facility. Very short lived exotic species can be obtained at ISOLDE, but current energies of reaccelerated beams make impractical their implantation in AstroBox.*
- **C2.5** *In 2013 the experiment RIBF13 approved by the RIKEN PAC at SAMURAI should take place. The preparations for this experiment (reactions with two different radioactive beams at 2 energies on light and heavy targets) will take a large part of the time. Part of the data will be analyzed in IFIN in 2014 and after.*
- **C2.6** *In the summer of 2014 a new edition of the Carpathian Summer School of Physics, the* 5^{th} *under the title "Exotic Nuclei and Nuclear/Particle Astrophysics. From nuclei to stars" will be organized. The organization will start one year earlier. Only seed funds for the school are asked for in this project, the rest will be sought later from internal and international bodies.*

C2.1 The PD returned to IFIN-HH in June 2012, as CS1 (Senior Researcher 1), more than a year before the financing of this project. A few month after, he could secure other funds from the institute to start hiring for his group. Dr. D. Chesneanu, CS (Research Scientist) at the time of hiring in Feb 2013, CS3 (Research Scientist 3) from the spring of 2014. Later two students were hired for part-time positions: Vicentiu Iancu (master student; in Aug. 2014 he left for France for an ELI-NP fellowship) and Iustinian Focsa (undergraduate student preparing his diploma thesis with us). Sebastian Toma (PhD student) joined in Sept. 2013. As such the group is within the proposed objective C2.1.

C2.2 The collaboration with dr. Carstoiu, which lasts for over 20 years continued. PD and dr. Carstoiu continued working together on subjects related to this project or on related projects. Of prime and immediate concern was to finalize by publication work which was done earlier, either at Texas A&M University or elsewhere. This resulted in 4 papers in 2014 alone [2-5].

C2.3 We continued working on subjects started earlier. As per the proposal, we continued to work on using the Trojan Horse Method (THM) with the group of prof. Claudio Spitaleri from the University of Catania and INFN-LNS, Catania, Italy. We did participate in one experiment with the Italian group at the LNS tandem in July 2013 and we had one experiment at the Bucharest tandem in June 2014. In preparation of the latter we had to make extensive adaptations to an existing large diameter target chamber. These changes were included in the proposal of this project and were done in collaboration with the DAT staff, but had to be supported with other funds. Both experiments were successful. Data are being analyzed for now by the Catania group. One of the students in our group (IF) will write a diploma thesis on the subject of Trojan Horse Method and will help in the analysis of the data collected in Bucharest.

C2.4 Another topic in which we have expertise is that of the study of resonances important in radiative proton capture using the inverse phenomenon of beta-delayed proton decay (βp). While at Texas A&M University we have pioneered this type of research. Currently we have design for a new detector, named ASTROBOX2, which was already realized, mounted and tested at TAMU. It was not yet tested in beam. I will get back to this in the next section of the report.

C2.5 Breakup experiment at RIKEN. In the contracted project it was re-scheduled for 2016. This did not take place yet. One reason is our lack of funding in most of 2013 for this purpose. Another, more important, is that the radioactive beam facility RIBF at RIKEN, Wako, Japan, functions only for a very limited time each year, for financial and energy reasons, especially after the catastrophic earthquake and tsunami of March 11, 2011. A proposal (code NP0906-RIBF13) in which breakup in nuclear and Coulomb fields was proposed for ^{9}C, ^{17}F and ^{27}P, all with NA motivation, was previously approved by the RINBF PAC, but expired. We had to prepare, in cooperation with our collaborators from Japan, USA, Italy and France, a renewal of this proposal. Importantly:

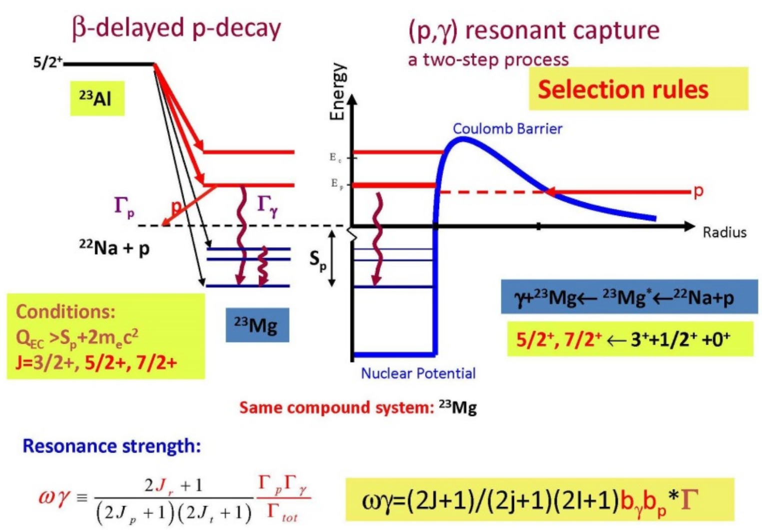
- due to scarcity of the beam time, we reduced the study to one projectile only, ^{9}C, for which the science case is stronger.
- We will use the newly commissioned spectrometer SAMURAI instead of the ZeroDegree spectrometer. SAMURAI gives by far better conditions. I have also worked for the last 4 years, in collaboration with groups from four US universities and our Japanese colleagues, for developing the detector system and associated electronics in front of SAMURAI, right after the target station. This proposal will be presented at the RIBF PAC on Dec. 12th, 2014, in Wako. It got the code NP1412-SAMURAI29R1 from the RIBF PAC organizers. In addition we are partners in breakup proposals which were inspired by our earlier work [6-9], codes NP1412-SAMURAI256R1 and NP1412-SAMURAI28 lead by groups from ATOMKI, Hungary and Louisiana State University, USA, respectively.

C2.6 We have organized successfully the 2014 edition of the Carpathian Summer School of Physics. The event has taken place between July 13-26 in Sinaia, Romania, as proposed in this project. Detailed report in the next section.

3. Specific objectives

3.1 Design and construction of the micromegas detector for AstroBox2. Measurements, data and nuclear structure calculations

While at Texas A&M University I focused on obtaining data for the resonant contributions in radiative proton capture reactions from the spectroscopy of those resonances. In particular we proposed to study the spectroscopy of states populated by β-delayed proton emission (βp). This is particularly useful for cases where the proton capture is dominated by resonances. The resonant capture of protons is a two-step process where the proton incident on a nucleus populates first a metastable state in the compound nucleus (1^{st} step) that then de-excites (2^{nd} step) by gamma-ray emission. The corresponding astrophysical reaction rates are given by the properties of the narrow, isolated resonances only: spin and parity, energy and resonant strength ωγ [10]. To study these resonances at astrophysical energies by direct measurements is not always easy or even possible. An alternative is to populate the same metastable states and determine their spectroscopic properties by other means. One way is the decay spectroscopy: we chose an exotic nucleus that will beta-decay to the same states. Important conditions must be met: $Q_{EC}>S_{p,}$ to have enough energy to populate states above the proton threshold in the daughter, and that the spin and parity selection rules allow to populate the states that are the important resonances. The relation between this decay spectroscopy studies and the proton capture reactions that occur through narrow, isolated resonances in stellar environments is presented in Figure 1 below. We will discuss here only the basics of the experiments, with emphasis on the best studied case: βp-decay of ^{23}Al.



$$\omega\gamma \equiv \frac{2J_r+1}{(2J_p+1)(2J_t+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_{tot}}$$

Figure 1. Schematic presentation of the relation allowing the use of beta-delayed proton decay in resonant proton capture.

3.1.1 The experimental technique. βp-decay of ^{23}Al

We have studied ^{23}Al β-decay before [11] using β–γ coincidence techniques. Secondary beam rates of about 4000 pps and >90% purity were obtained with the MARS spectrometer [12]. The states populated in ^{23}Mg above the proton threshold at S_p=7580 keV can decay by proton emission. They are resonances in the proton capture reaction $^{22}Na(p,\gamma)^{23}Mg$, crucially important for the depletion of ^{22}Na in ONe novae. The novelty of our approach consist in that that instead of the usual technique of separating the unstable nucleus, depositing it on/in a surface and then measuring its decay with an external detector, we chose to implant the unstable ^{23}Al nuclei in the middle of a detector and then measured its decay. A setup consisting of a thin Si double-sided strip detector (DSSD) (p-detector, 65 μm, 16x16 strips) and a thick Si detector (β-detector, 1 mm) was used in the present experiment. A HPGe detector outside the chamber has detected the γ-rays. We have pulsed the beam from the cyclotron, implanting the source nuclei in the thin Si detector (for about 2 lifetimes), and then switched the beam off (same duration) and measured simultaneously β–p and β–γ coincidences. In order to reduce to a minimum and control the implantation depth we have restricted the momentum spread of the incoming ^{23}Al nuclei to about ±0.25% and the beam rate to about 500 pps. This has been done by closing down the momentum defining slits in MARS. The implantation depth was controlled using a rotating energy-degrader aluminium foil in front of the Si telescope. Implantation distributions of the order of 17 μm deep were obtained. After β-decay either gamma or proton decay follows. All protons emitted with energies below 1.5 MeV stop in the thin Si strip detector and give sharp peaks. The positrons (emitted before) leave a small signal of continuum spectrum in the same thin detector that adds to the proton signal to produce a skewing of the proton peaks on the high energy side and degrade the resolution. For those (majority) cases where gamma rays are emitted instead, the positrons give a large background at low energies in the p-detector. To reduce this background and the degradation of the resolution it was essential to make the proton detector as thin as possible and the volume of the detector as small as possible (narrow strips). Almost half of the emitted positrons end up in the thick detector behind and trigger the acquisition when a gamma ray or a proton signal arrives in coincidence. Data on the β-delayed proton decay of ^{23}Al existed before, but were obtained with less intense sources and at times were contradictory. The most remarkable result is that we have located the most important resonance in the $^{22}Na(p,\gamma)$ reaction at E_{cm}=207 keV and we able to measure both its proton and gamma-branching, a rare, if not unique case (published elsewhere [13, 14]). Another remarkable result of the current measurement was obtained while implanting ^{21}Mg in the middle of the p-detector. With a production rate of about 1 pps, we could obtain a reasonable spectrum in about 8 hrs of experiment. This shows the sensitivity and selectivity of our method.

3.1.2 Astrobox 1, results and the new Astrobox2 detector

However remarkable our results using detectors as thin as possible (65 μm, then 45 μm) were, the measurements suffered from a very high background in the region of low energy protons, below 400 keV, e.g., due to the continuum signal left in the Si detectors by the overwhelming number of positrons, present at each decay. While protons have branchings of $10^{-3} – 10^{-4}$ or even lower. In order to diminish this background we chose a detection medium less sensitive to positrons: gas (P10). In the same time, we chose a technique which allows significant signals from so low energy deposits: the so called micromegas [15]. The detector was named ASTROBOX1 (Figure 2) and the technique was successfully applied to the case of ^{23}Al and published in 2013 [16].

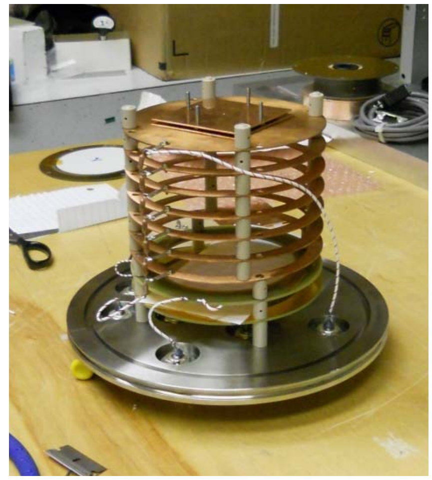


Figure 2. Picture of AstroBox1 from pre-experiment setup. Beam enters perpendicular on cylinder axis.

As in the case of Si detectors, the incoming radioactive specie is stopped in the middle of the (gas) detector by bombardment using the same energy degrader as before ("implantation mode"), then the beam is stopped and the detector goes into a "measuring mode", characterized by a higher gain and high resolution. A spectrum obtained with the Si detector is shown in Figure 3 and for comparison one with Astrobox1 in Figure 4. It is obvious that the continuum background due to positrons was reduced down to energies below 80-100 keV, making Astrobox1 ideal for the study of proton resonances in the region E_p=100-400 keV, where they occur in most astrophysical (p,γ) processes.

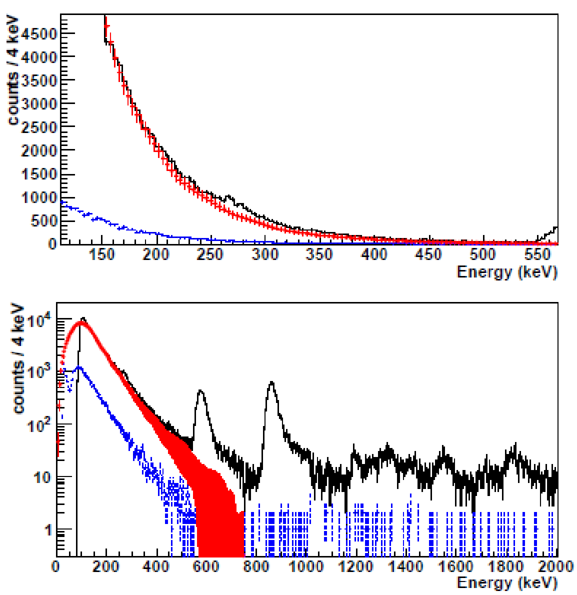


FIG. 7: (Color online) Full collected statistics for the ^{23}Al data (black, solid) and the ^{22}Mg data (blue, dashed). The energy is the total measured decay energy. Smoothed ^{22}Mg spectrum, scaled to match the ^{23}Al spectrum at 150 keV is shown with red dots and corresponding uncertainties. Upper panel shows only the low energy part where the proton group at ∼ 270 keV is clearly visible on top of the β background, whereas the lower panel shows the total spectra.

Figure 3. Spectra from the βp-decays measured with a 65mm thin Si detector. From Ref. [14].

However, we considered that this detector can be improved and a newer, more elaborate design was conceived in the last year: Astrobox2. The active part of the detector has a rectangular geometry, better for the geometry of the experiment. It is shown in Figure 5. At this moment the detector parts were built by a collaborative effort: micromegas at Bucharest-CERN-Saclay, the body of the detector at TAMU, the electronics in Bucharest, the gas handling system at TAMU. It was assembled in Oct. 2014 at Texas A&M University, where it was also tested with sources. The results show that it works in the expected parameters. No test in beam was possible due to lack of beam time at the K500 superconducting cyclotron of TAMU. The next beam time was promised (but not yet scheduled) for April 2015.

An overall picture of the new detector and the first results can be seen in the 3 pages immediately after this report (before Annexes, pages 17-19 of the pdf file).

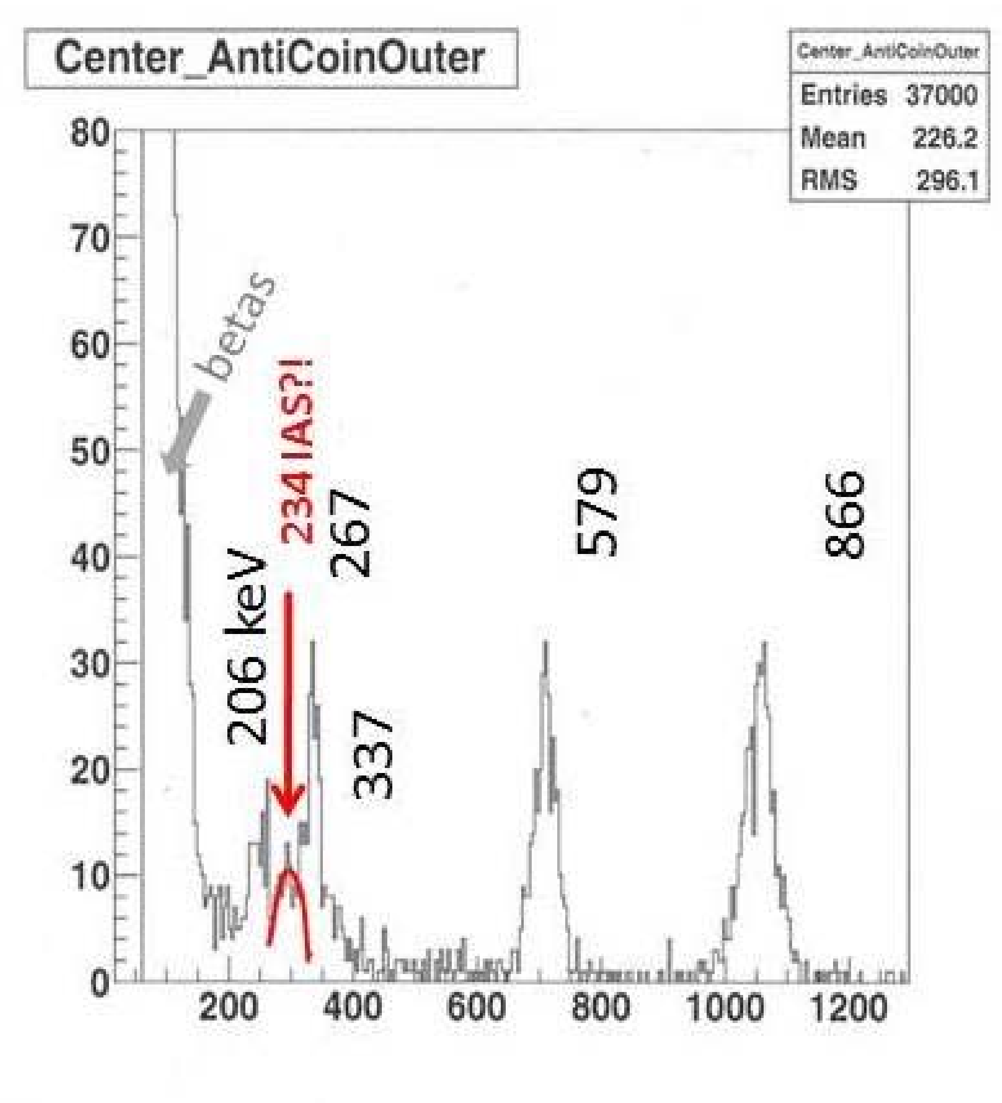


Figure 4. Spectrum taken with the Astrobox1 detector [16].

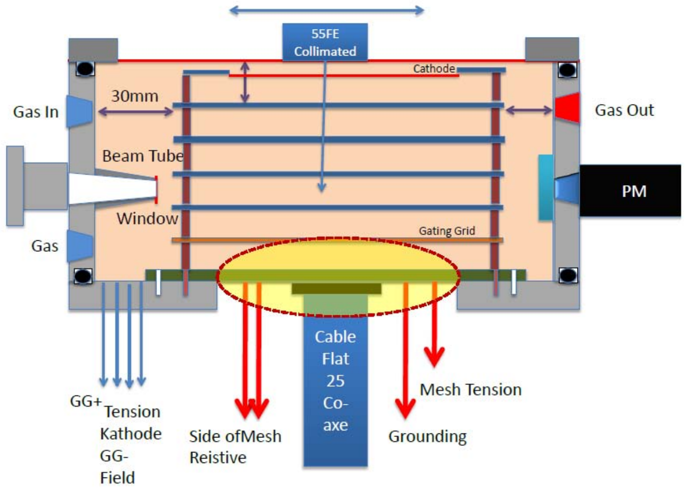


Figure 5. layout of the micromageas in Astrobox2.

3.1.3 Isospin mixing in ^{23}Al

The story about isospin mixing in not directly related to NA, but is interesting as it was enticing us to complete the spectroscopy of βp-decay of ^{23}Al and seek better detection techniques, like those with Astrobox1 and 2. Simply put it goes like that:

- as in β-decays where this is energetically possible, the isospin T=3/2, $J^{\pi}=5/2^{+}$ g.s. of ^{23}Al populates very well the isobar analog state (IAS) in the daughter nucleus ^{23}Mg. It has T=3/2, not T=1/2 as all neighboring excited states in ^{23}Mg. We located it at E_{exc}=7803 keV by measuring its log*ft*= 3.31(3), fully consistent with a pure Fermi transition. It is only 16 keV higher in excitation energy than another state of regular isospin at E_{exc}=7787 keV, of spin $J^{\pi}=5/2^{+}$ or $7/2^{+}$ (most probably $7/2^{+}$).

- Proton decay of the IAS is isospin forbidden to ^{22}Na*+p, T=1/2 states, but an experiment of the famous Berkeley group in the 90's claimed to have identified that decay, which would only take place due to an isospin mixing in the IAS which is 50 times stronger than expected from best nuclear structure calculations [17].

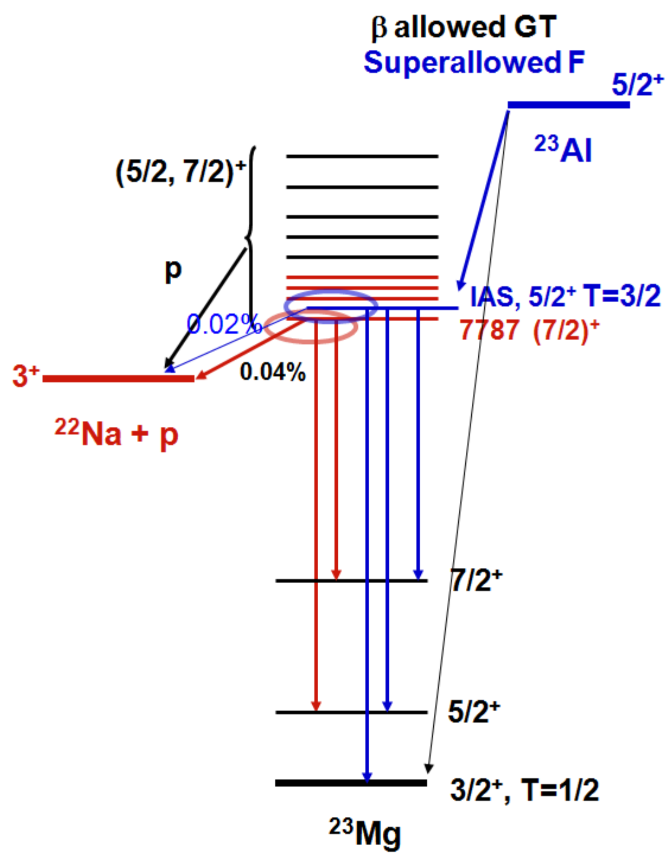


Figure 6. Scheme of 23Al β- and βp-decay.

Our β–γ measurements [11] and those with ^{23}Al implanted in Si detectors have shown that the measurements of the Berkeley group at low energies were wrong, but even our measurements with ^{23}Al implanted in thin Si detectors could not establish a good limit of the isospin mixing due to the strong background at low proton energies due to competitive positron signals (figure 3). We found though that the lower T=1/2 state at E_{exc}=7787 keV decays by proton emission and by gamma emission [11]. However, our Astrobox1 measurements could find the very small peak in the proton spectrum and from its relative intensity that decay is fully consistent with a very small isospin mixing, of the order of that calculated using best sd-shell parameters of BA Brown [18]. This result is not yet fully published, in expectation of even better results for our future measurements with Astrobox2. Further uncertainty, both in calculations and in the interpretation is due to the uncertain spin of the lower state. A spin $J^{\pi}=7/2^{+}$, the most probable, simplifies the interpretation, but a $J^{\pi}=5/2^{+}$ spin complicates it, as even small mixing matrix elements between these two states are much more difficult to control and reproduce by calculations.

3.2 Carpathian Summer School of Physics 2014

The Carpathian Summer School of Physics 2014 was organized in Sinaia, July 13-26, 2014. It was the 26th edition of a tradition that begun in 1964 and the fifth in the series dedicated to nuclear and particle astrophysics, in relation to nuclei and to physics of exotic nuclei in particular. This is already a 50 years tradition. Therefore we also (modestly) celebrated the jubilee of the Carpathian schools this year. The title of the event was:

"Exotic Nuclei and Nuclear/Particle Astrophysics (V). From Nuclei to Stars”

and is the **5th** in the latest series with the same title organized in Mamaia (2005) and Sinaia (2007, 2010 and 2012). It was hosted again in Sinaia, on the facilities of hotel ”International”.

The Carpathian school is part of the European Network of Nuclear Astrophysics Schools (ENNAS), together with the **European Summer School on Experimental Nuclear Astrophysics, ESSENA** (Santa Tecla, Italy) and the **Russbach School on Nuclear Astrophysics, RSNA** (Russbach am Pass Gschütt, Austria). In agreement with those schools' organizers, we created an established network of periodic events that responds to the need of preparing and educating the younger generations of physicists in the cross disciplinary fields of nuclear physics and astrophysics. The organizers were, as in the past 5 editions:

"Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH) Bucharest and **the Cyclotron Institute, Texas A&M University (TAMU), College Station, Texas, USA.**

As in the past editions also, the **first week** of the event had a school-like format defined by a series of courses 1- 2 hours each. It was being aimed at graduate students, post-docs and young researchers. About 55 students from the host country, the surrounding regions and all countries attended. A number of stipends (22) to cover the local expenses for students were available and established following the rules spelled out in our announcements. The **second week** had a conference-like format, closer to the past format of all Carpathian schools, with 1 hour invited lectures. Students and young researchers gave 20 min. short communications, both weeks.

The sessions of CSSP14 covered the following topics, set by the organizers after consultation with the other directors of ENNAS and advise from an extended International Advisory Committee:

- **Exotic nuclei**
- **Nuclear physics with RIBs**
- **Nuclear physics for astrophysics**
- **Neutron stars and EOS**
- **Issues in nuclear astrophysics & nucleosynthesis**
- **Stellar evolution. Compact stars and supernovae**
- **Neutrino physics**
- **Astroparticle physics**
- **Stellar and laser induced plasmas**
- **Physics at ELI-NP**

We intended to bring to this audience news about the **Extreme Light Infrastructure – Nuclear Physics (ELI-NP)**, the newest and most important scientific project that happens in the host country and the region. Therefore, Thursday-Friday July 17-18 the school included the ***International Conference "ELI-NP. Status and Perspectives"***.

A special outreach day was being planned for **Saturday July 19th**. The morning session gathered lectures addressing a broader audience like that of prof. K.-L. Kratz, this years' Bethe prize winner, and the charming lectures of S. Bishop (a nuclear physicist) and R. Egli (a geologist) on looking in the depth of the planetary ocean for signs of a supernova explosion in the past in our galactic neighborhood! The afternoon session was held in a, by now traditional, round table format. The subject chosen this year was:

“CERN at 60 and the internationalization of science”

The day was honored by the presence of prof. Rolf Heuer, director general of CERN, prof. Tudor Prisecaru, MEN state secretary, other officials of the host country involved in the research policy and in the management of research and higher education, by CERN, FAIR, and ELI officials, scientists working at CERN, FAIR and ELI-NP, politicians and representatives of media invited to join the CSSP14 participants in open discussions on the above subject. The session was followed by the school’s banquet that evening and by the school excursion(s) on Sunday, July 20^{th}. A short overview of the interventions at this session and the lecture of professor Heuer are included in Part III of this volume.

Sponsors of the school were *the two organizing institutions*, the *Romanian Ministry of National Education (MEN)*, ENSAR through *the ATHENA network*, the *Nuclear Astrophysics Virtual Institute (NAVI)* and the exhibitors *iGroup, CAEN* and *Canberra*. The event was endorsed by the European Physical Society, through its Nuclear Physics Board. Most of the participants were supported by their respective institutions, a fact which contributed to existence and the success of the school and which makes these institutions be our sponsors too. We thanks them all!

We have attracted at the peak of participation on Saturday-Sunday July 19-20, approximately 120 people, of which 52 from outside Romania. There were 59 lecturers who gave 65 lectures in the two weeks. As organizer of the latest 5 editions of the school with this title, I can say that this was probably the most successful, in terms of number and quality of participants and lectures/debates. I mention that we had 31 communications from students and young researchers, compared to 19 in the previous edition (CSSP12).

Due to reduction of funds for 2014, we avoided using resources from this project and used only 4521 RON for Carpathian school’s organization. Most of the funds were attracted from outside: 10,000 euro from ATHENA, a network of ENSAR, 5,000 euros from NAVI, 4600 euros from exhibitors CAEN, IGroup and Canberra, 7,500 RON for the Ministry of National Education, Bucharest. In our integrated financial report to MEN, we evaluated that the total cost of the event was 234.060 RON, not including the expenses of the participants who use own institutions’ funds for accommodation and meals.

I attach here the reports sent to the sponsors ATHENA, NAVI and MEN (in Romanian) after the school.

The volume of the Proceedings is ready and was already submitted for publication to the American Institute of Physics, New York [19]. In its over 400 pages it contains 30 lectures and

30 communications. It should be published online before the end of the year 2014, and in print at the beginning of 2015. We include, attached, the list of articles in the volume of the Proceedings.

4. Related activities and achievements

A number of activities and achievements related to the main scientific motivation of this project must be outlined here. They are related to the constant work to obtain, then increase, the visibility of a nuclear group working in nuclear astrophysics in IFIN-HH. These were on two directions, intertwined in fact:

1. Creating and testing the experimental capabilities for nuclear astrophysics in Bucharest. This was done by experiments at the 9 MV tandem, but especially at the new 3 MV tandetron of IFIN-HH.
2. Creating and promoting the visibility of the NA research in IFIN-HH, and promotion of the potential in European context, which should attract outside users for our facilities 9and allow therefore, for justified reciprocity). This was done by participation to a number of international conferences, schools and workshops, in particular of the PD, who used his existing prestige and recognition from the previous decades of activity in this field of research.

4.1 Direct measurements for NA at the 3 MV tandetron of IFIN

With the final goal of establishing a solid line of research in nuclear astrophysics (NA) at the Bucharest accelerators and laboratories of IFIN-HH, we have performed experiments to check the limits of one method that seems appropriate and for which the institute has or could acquire installations: the activation method. We used for irradiation the new 3 MV tandetron accelerator. It was tested in 2013 that this accelerator can provide good intensities for alpha particles and light ions, and that these intensities are stable for long experiments as those in direct NA measurements tend to be. We noted that while there are many small proton accelerators used specifically for NA, some underground (like LUNA in LNGS, Gran Sasso, Italy or DIANE project in USA) not many accelerators for alpha and light ions are dedicated to NA direct measurements. This could be the niche of our laboratory. This year we tested this accelerator's possibilities, together with the existing low and ultralow background laboratories of IFIN-HH, situated above ground and underground, respectively, for activation measurements. We have chosen the $^{13}C+^{12}C$ reaction, which leads to an activation appropriate for our tests: ^{24}Na, with a half-life of 15.0 hrs, formed by one proton evaporation. First tests were done in the period May-June 2014. We studied the $^{12}C+^{13}C$ fusion reaction in the energy range $E_{c.m}$ = 2.9 - 3.8 MeV using the activation method and gamma-ray spectroscopy. Activities of irradiated targets measured both in the underground and surface laboratories allowed to determine the limit of detection of cross sections to be of the order of 1-3 nb. By increasing the intensity it is possible to gain a factor of 10 in sensitivity and by using $\beta-\gamma$ coincidences, another factor of 10. However, this will imply a good cooling of the graphite targets. Calibrations and measurements performed in identical or similar conditions will also allow us to reduce the uncertainties associated with the experimental data corresponding with range $E_{c.m} = 2.6\text{-}5.0$ MeV below 20%, and to determine the cross section for the $^{12}C+^{13}C$ process at an energy lower than $E_{c.m} = 2.6$ MeV. The successful results of the tests were presented as a communication at CSSP14 by dr. D. Chesneanu, a member of our group. Essentially, we found that we can increase the sensitivity of these measurements by about a factor 100. The communication [20] is included in the volume of the Proceedings of CSSP14, published by the American Institute of Physics under its Conference Proceedings Series, an ISI recognised publication. It is attached to this report.

Starting from those results in October 2014 our group, together with a group from IMP Lanzhou, China, we have continued the work, taking the test into an full-fledged experiment. The data obtained are not fully analysed at the time of this report, but we can say that they confirm the assessments from the May-June tests, and that the measurements were already taken to energies lower than any measured before in the world. The experiment will continue and the data will be published in peer-reviewed journal(s). The focus will be this time on certification of the absolute values of the cross sections and on going further down in bombarding energy.

4.2 Participation to conferences, schools and workshops in NA. The ELAN European project

A number of participations of members of our group in conferences, schools or workshops were related directly to creating and improving the visibility of NA research at IFIN-HH, the very subject of this proposals. This is the case mostly for the seniors of the group, in particular of my-self, as PD. The juniors and students were participating to learn, mostly. As such, the project director was invited in 2013 and 2014 to many conferences, meetings, workshops and schools dedicated to nuclear astrophysics or related to it. Several of those were financed from this project, but not all. In aprticular I was asked to talk or lecture about the use of indirect methods in Nuclear Astrophysics using radioactive nuclear beams. I indicate them in the list below, specifying the website where the material was/is posted:

- 10th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 2013. Invited lecture: "Decay spectroscopy for nuclear astrophysics". http://russbach-wks.sciencesconf.org/resource/page/id/12
- The EURISOL User Group Topical Meeting, Krakow, July 1-3 2013, http://eurisol.ifj.edu.pl/. Invited talk: "Rare isotope production and ELI-NP".
- International Workshop in Nuclear Dynamics in honor of prof. J.B. Natowitz, Texas A&M University, College Station, TX, USA. Aug. 22-25, 2013.
- The APS town meeting at NSCL, East Lansing, MI, USA. 25 Aug. 2013.
- 2nd International workshop on quasi-free scattering with Radioactive-Ion Beams, QFS13, Azores Islands, Portugal. Sept. 15-21, 2013. Invited talk: "Experiments on Direct Reactions with Light Radioactive Beams [for nuclear structure, reaction mechanisms and nuclear astrophysics]". http://cfnul.cii.fc.ul.pt/events/QFS-RB13/.

- 7th European Summer School on Experimental Nuclear Astrophysics, St. Tecla, Italy. Sep. 15-25, 2013. Invited lecture: "Decay spectroscopy for nuclear astrophysics and conditions created by one **E**xtreme**L**y hot **I**nfrastructure for **N**uclear astro**P**hysics". https://agenda.infn.it/conferenceDisplay.py?confId=5302
- ECOS-LINCE Workshop, University of Huelva (Spain), 30-31 October, 2013; invited talk: "Nuclear astrophysics using high intensity stable beams". http://indico.cern.ch/event/263009/?ovw=True
- Texas Symposium on Relativistic Cosmology, Dallas, TX, USA. Dec. 9-13, 2013. Invited talk.
- 11th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 9-15, 2014. Invited lecture: "Nuclear astrophysics at ELI-NP". http://russbachwks2014.sciencesconf.org/
- Final ATHENA workshop at Villa Vigoni, Italy. May 13-16, 2014. Invited lecture.
- Nuclei in Cosmos NIC XIII school, Debrecen, Hungary. June-July 2014. Invited lectures: "Experimental nuclear astrophysics (stable beam experiments)". http://www.atomki.hu/nic2014school/program.html
- International Olympiad Astronomy & Astrophysics, Universitatea "Stefan cel Mare" Suceava, Romania. Invited talk at outreach event: "Chemical origin of chemical elements".
- APS town meeting on the new Long Range Plan, Texas A&M University, College Station, TX, USA. Aug. 2014.
- ECT* workshop Nuclear Physics and Astrophysics of Neutron-Star Mergers and Supernovae, and the Origin of R-Process Elements" Trento, Italy, Sep. 8-12, 2014. Invited talk and organizer. http://www.ectstar.eu/node/788
- Notre Dame-Europe Symposium on Nuclear Science and Society, London, Oct. 27-29, 2014. Invited talk: "Study and preservation of cultural heritage with atomic and nuclear techniques at IFIN-HH Bucharest". http://isnap.nd.edu/events/NSS2014/

Dr. Daniela Chesneanu has participated and presented communications at the 7th European Summer School on Experimental Nuclear Astrophysics, St. Tecla, Italy. Sep. 23-25, 2013 and at the Carpathian Summer School of Physics 2014.
The students attended schools on our research subjects: the JINR Dubna school in Borovets, Bulgaria (both VI and IF) and the CSSP14 Sinaia (V. Iancu, with a fellowship, only minor support from this project).

One particular achievement should also be noted: the group is already noticed at European level. As recently as in the fall of 2014 n Horizon2020 project was proposed by an "emerging community" under the title European Laboratory Astrophysics Network (ELAN). In this community, the tandem accelerator complex at IFIN-HH was proposed a Transnational access facility (TNA) for 2015-19, an activity coordinated by the PD of this project. The proposed amount is 150k euro.

5. Conclusions

From the above report and documents attached, we conclude that the objectives for the first 14 months of this project were fulfilled in both spirit and letter. Some of the activities proposed over 2.5 years ago could not be done in their letter, due to the fact that they are affected not only by local parameters, but by external ones, like availability of beam time at large RNB facilities (RIBF at RIKEN, Japan and MARS at TAMU, USA), and possibly, by shifts in the short term tactics, while keeping the focus of the strategy of research: nuclear astrophysics in IFIN-HH.

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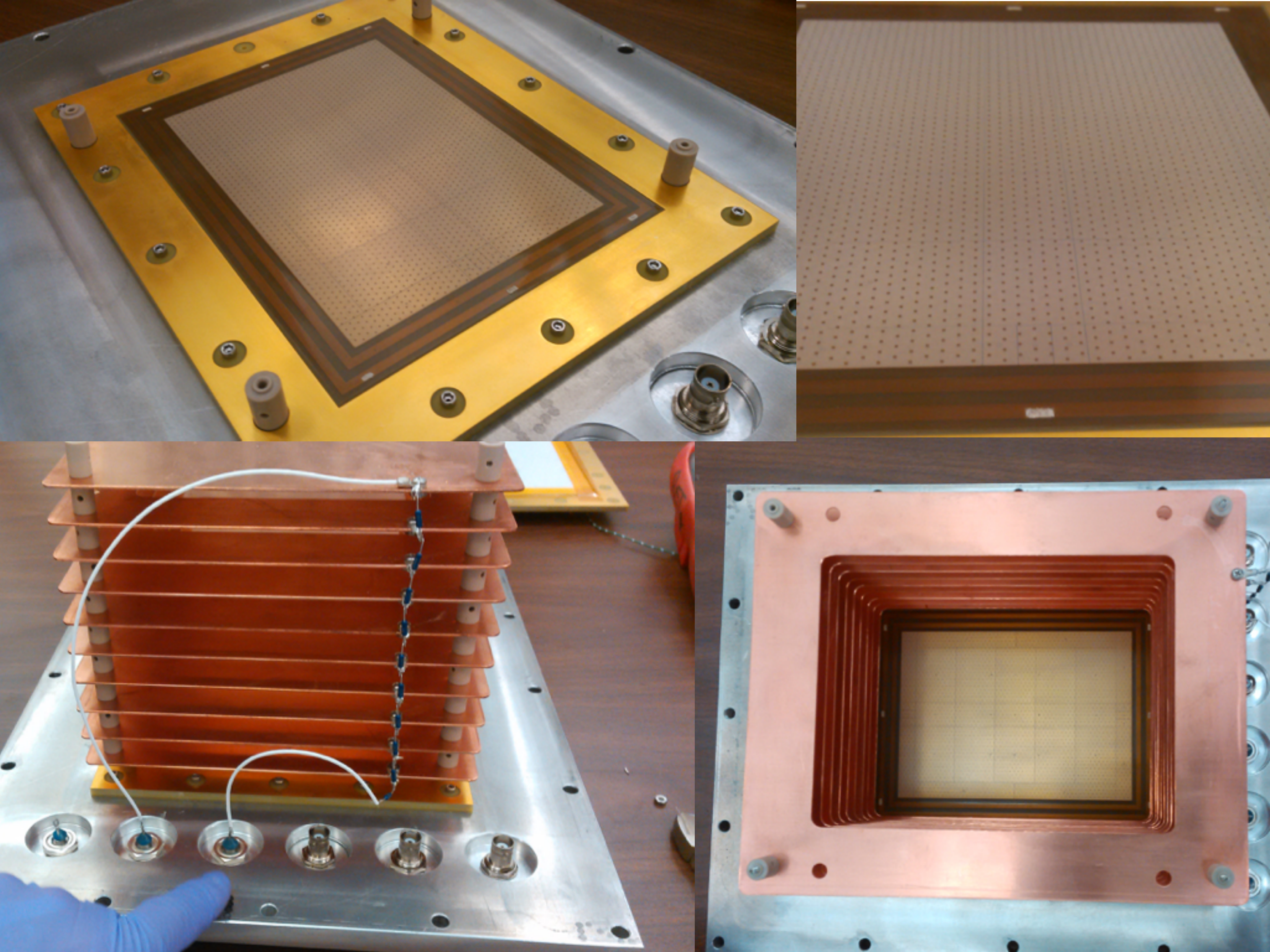
Consideram ca obiectivele acestei faze au fost integral indeplinite.

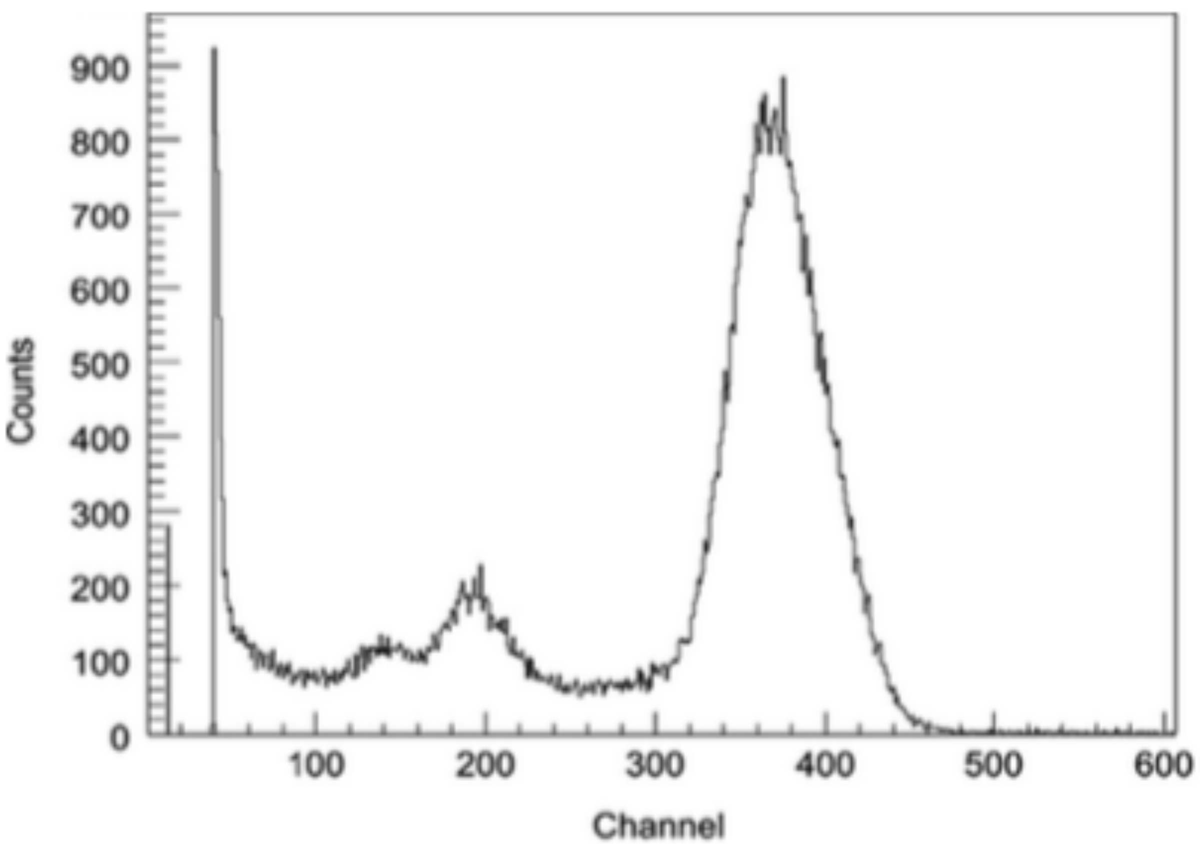
Responsabil Proiect
Dr. Livius Trache

Responsabil Etapa
Dr. Livius Trache



^{55}Fe source

AstroBox1



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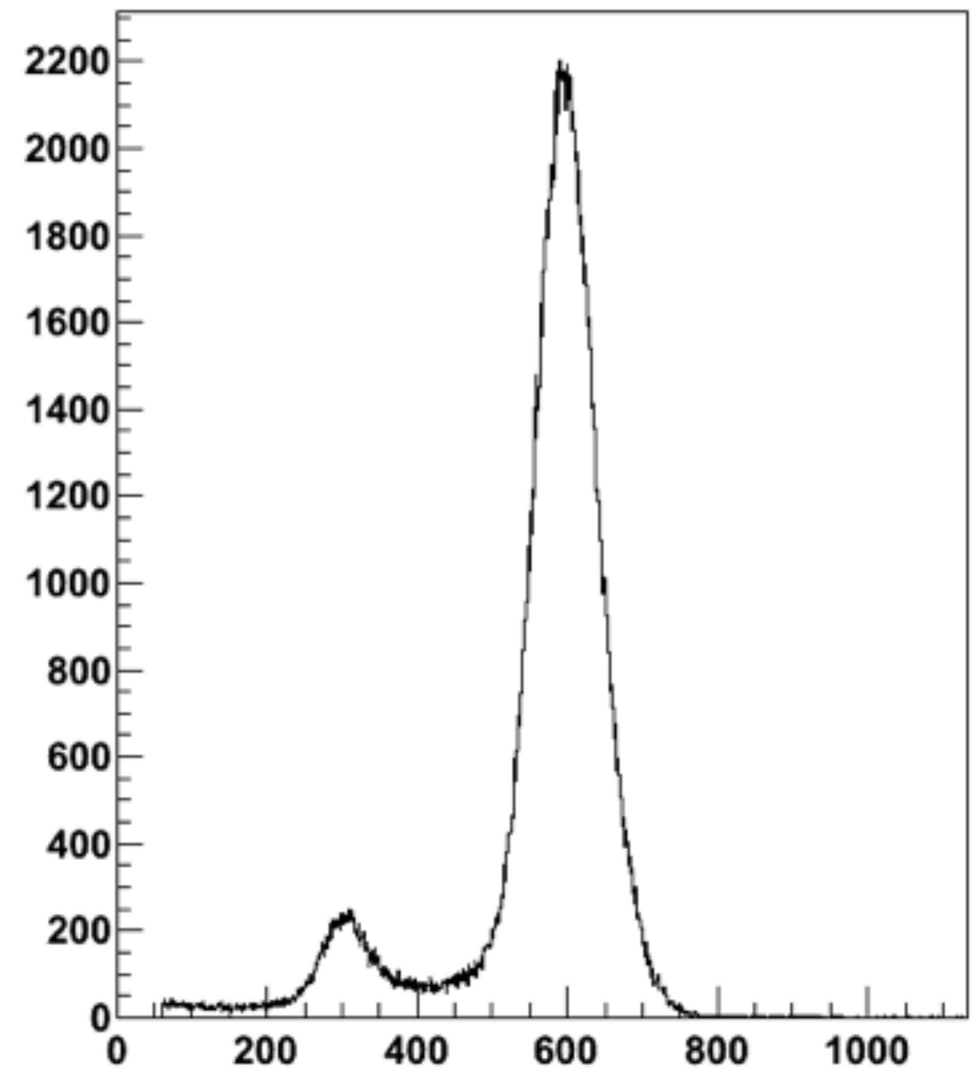
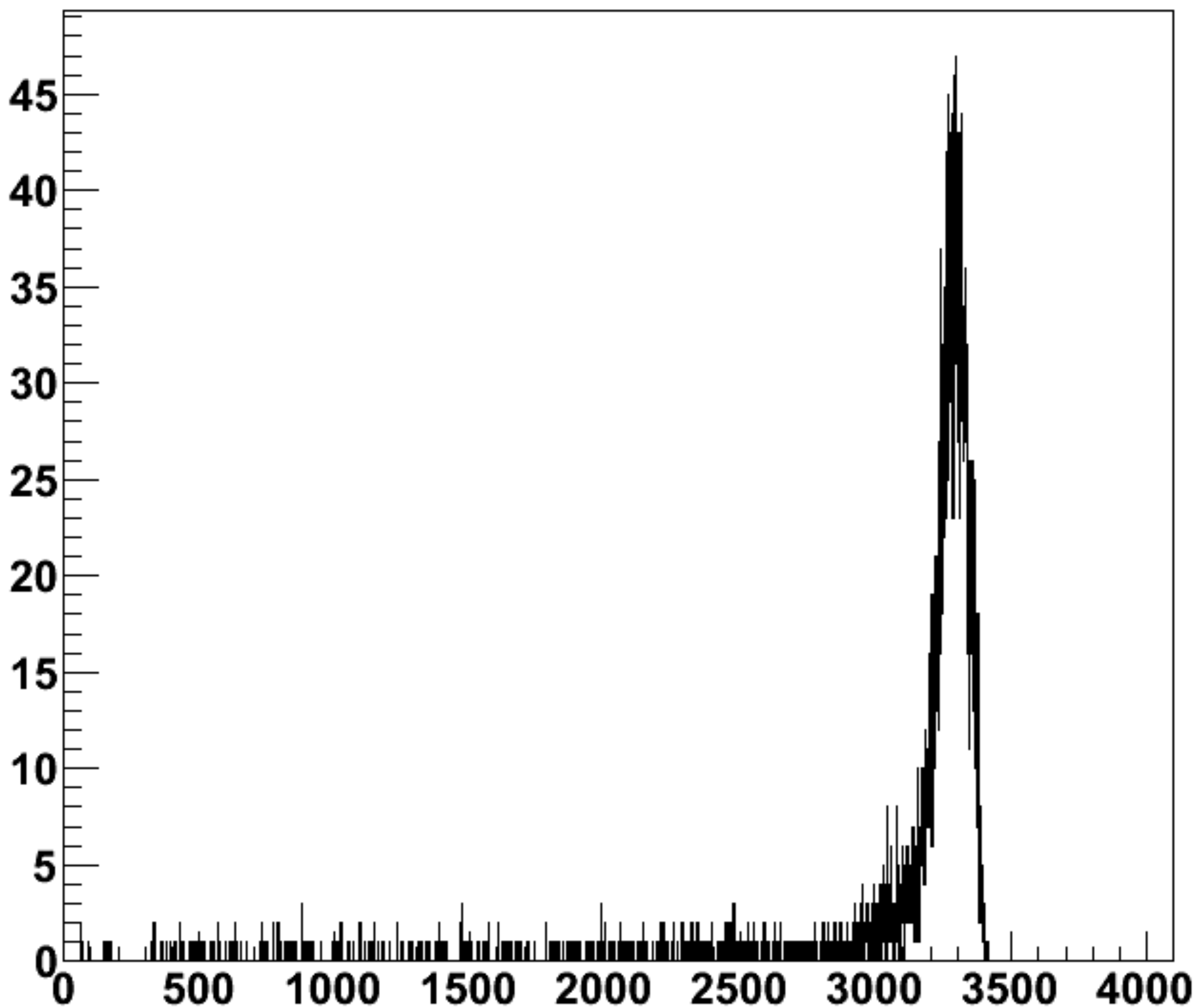


Astrobox 2 - views and results of the first test with sources. TAMU, Oct. 2014

^{241}Am source



IFIN-

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

Carpathian Summer School of Physics 2014

Exotic Nuclei and Nuclear/Particle Astrophysics (V)

"From nuclei to stars"

July 13 - 26, 2014, Sinaia, Romania

Report to ENSAR ATHENA

In the period July 13-26, 2014, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania (IFIN-HH) and the Cyclotron Institute, Texas A&M University, College Station, TX, USA organized the Carpathian Summer School of Physics 2014 (CSSP14). It was the 26th edition of physics summer schools in the Carpathians and the 5th edition with the title "Exotic Nuclei and Nuclear/Particle Astrophysics (V). From nuclei to stars". It was hosted in Sinaia, Romania, on the facilities of hotel "International". See the website http://cssp14.nipne.ro for more details.

Sponsors were the two organizing institutions and the Romanian Ministry of National Education (MEN), ENSAR through the ATHENA network (10,000 euro), Nuclear Astrophysics Virtual Institute NAVI (5,000 euro) and exhibitors iGroup (1500 euro), CAEN (1000 euro) and Canberra (1600 euro). The event was endorsed by the European Physical Society, through its Nuclear Physics Board and is part of the European Network of Nuclear Astrophysics Schools (ENNAS). Most of the participants were supported by their respective institutions, which contributed to the success of the manifestation.

The event had, as by tradition, a mixed format of school (mostly the first week) and conference.

Thu-Fri July 17-18 it included the International Conference "ELI-NP. Status and Perspectives". On Saturday July 19th a special outreach session on "CERN @ 60 and the internationalization of science" was honored by the presence of prof. Rolf Heuer, dir gen of CERN, prof. T. Prisecaru, MEN state secretary, other academics, public and media representatives.

There were in total ~100 participants from 4 continents (of which 52 from outside Romania).

59 invited lecturers presented 65 lectures of one hour each.

Students at the school presented a total of 31 communications of 20 minutes each.

The proceedings of CSSP14 will be published in the Conference proceedings series of AIP.

The fellowships were granted following students' applications made by email or on the website of the event (http://cssp14.nipne.ro). The applications consisted of a CV and a recommendation from their advisor; were received by the Organizing Committee before April 15 2014 and a total of 22 fellowships were decided and announced at the beginning of May. Most, but a few of the lecturers, and the rest of the students were supported by their own institutions.

MINISTERUL EDUCAȚIEI NAȚIONALE

ATHENA

NAVI
Nuclear Astrophysics Virtual Institute

EPS

This is a report to ENSAR ATHENA network about the use of the 10,000 (ten thousand) euro funds generously provided for CSSP14

The funds were used directly to support students (7,400 euro) and a few lecturers (2,550 euro). The remainder 50 euro was put in the general pool used to cover other organizational costs.
The costs for lecturers consisted of accommodation only at 60 or 75 euro/day.
The costs for students consisted of:

- Accommodation at 33.5 euro/day/person in double occupancy hotel rooms or at ~ 27 euro/day/person at a nearby "pensiune" (including breakfast)
- Conference fee at 350 euro for full two weeks stay or 200 euro for one week, covering lunches, coffee breaks and some incurring costs for birotica
- Transfer between the airport in Bucharest and Sinaia (~110 km), at 25 euro/person/trip.
- Cost of the volume of the conference proceedings, contracted with the American Institute of Physics Conference Series.

No international transportation costs were covered.
Lecturers supported from NAVI funds were:

1. Carlos Bertulani (Texas A&M University)	8 days	600 euro
2. Karl-Ludwig Kratz (Inst.fuer Kerchimie, Mainz)	9 days	675 euro
3. James Lattimer (State Univ.New York)	4 days	300 euro
4. Marek Pfutzner (Univ. of Warsaw)	6 days	450 euro
5. Octavian Sima (Univ. Of Bucharest)	7 days	525 euro

A number of 12 students were covered:

1. Nicusor Arsene (IFIN-HH)	13 days	750 euro
2. Anna Caruso (Univ. di Catania)	13 days	750 euro
3. Ghina Mahmoud-Halabi (American Univ.of Beirut)	6 days	450 euro
4. Iulia Harca (JINR-IUCN, Dubna)	13 days	750 euro
5. Cristina Oancea (Univ. Of Bucharest)	13 days	750 euro
6. Sara Palmerini (INFN, Catania)	3 days	250 euro
7. Sebastiana Puglia (INFN, Catania)	5 days	350 euro
8. Partha Roychowdhury(Dept.of Physics, Kampalur)	13 days	750 euro
9. Simone Sanfilippo (Univ. Di Catania)	3 days	750 euro
10. Maria Letizia Sergi (INFN, Catania)	7 days	350 euro
11. Shota Shibagaki (Univ. of Tokyo)	13 days	750 euro
12. Onofrios Sgouros (Univ. of Ioanina)	13 days	750 euro

Total: 9950 euro
Other expenses: 50 euro
Grand total: 10,000 euro
No VAT was paid from this source.

Other 10 students were supported from the funds sponsored by NAVI and the exhibitors.
We attach the epitome of the two weeks of the school. 12 receipts signed by the above 12 students are attached, scanned, or in original (if requested). All the above students have presented communications at the school/conference. The schedule of their communications is also included.
The logos of sponsors, including that of ATHENA, were prominently displayed on the website and during the event, and the students supported were advised to acknowledge their sponsor in the papers submitted for the volume of the Proceedings.

Dr. Livius Trache (IFIN-HH)
Chair, CSSP14 Organizing Committee

Ec. Alexandra Olteanu (IFIN-HH)
CSSP14 Financial Director

Carpathian Summer School of Physics 2014

Exotic Nuclei and Nuclear/Particle Astrophysics (V)

"From nuclei to stars"

July 13 - 26, 2014, Sinaia, Romania

Report to Nuclear Astrophysics Virtual Institute (NAVI)

In the period July 13-26, 2014, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania (IFIN-HH) and the Cyclotron Institute, Texas A&M University, College Station, TX, USA organized the Carpathian Summer School of Physics 2014 (CSSP14). It was the 26th edition of physics summer schools in the Carpathians and the 5th edition with the title "Exotic Nuclei and Nuclear/Particle Astrophysics (V). From nuclei to stars". It was hosted in Sinaia, Romania, on the facilities of hotel "International".
Sponsors were the two organizing institutions and the Romanian Ministry of National Education (MEN), ENSAR through the ATHENA network (10k euro), Nuclear Astrophysics Virtual Institute NAVI (5k euro) and exhibitors iGroup (1.5k euro), CAEN and Canberra (1k euro each). The event was endorsed by the European Physical Society, through its NPB and is part of the European Network of Nuclear Astrophysics Schools (ENNAS). Most of the participants were supported by their respective institutions, which contributed to the success of the manifestation.
The event had, as by tradition, a mixed format of school (mostly the first week) and conference.
Thu-Fri July 17-18 it included the International Conference "ELI-NP. Status and Perspectives".
On Saturday July 19th a special outreach session on "CERN at 60 and the internationalization of science" was honored by the presence of prof. Rolf Heuer, dir gen of CERN, prof. T. Prisecaru, MEN state secretary, other academics, public and media representatives.

There were in total ~100 participants from 4 continents (of which 52 from outside Romania).
59 invited lecturers presented 65 lectures of one hour each.
Students at the school presented a total of 31 communications of 20 minutes each.

The fellowships were granted following students' applications made by email or on the website of the event (http://cssp14.nipne.ro). The applications consisted of a CV and a recommendation from their advisor; were received by the Organizing Committee before April 15 2014 and 22 fellowships were decided and announced at the beginning of May. Most, but a few of the lecturers, and the rest of the students were supported by their own institutions.

This is a brief report to NAVI about the use of the 5000 (five thousand) euro funds generously provided for CSSP14

The funds were used directly to support students (3900 euro) and a few lecturers (975 euro). The remainder 125 euro was put in the general pool used to cover other organizational costs.

The costs for lecturers consisted of accommodation only at 75 euro/day.
The costs for students consisted of:

- Accommodation at 33.5 euro/day/person in double occupancy hotel rooms or at ~ 27 euro/day/person at a nearby "pensiune" (including breakfast)
- Conference fee at 350 euro for full two weeks stay or 200 euro for one week, covering lunches, coffee breaks and some incurring costs for birotica
- Transfer between the airport in Bucharest and Sinaia (~110 km), at 25 euro/person/trip.
- Cost of the volume of the conference proceedings, contracted with the American Institute of Physics Conference Series.

No international transportation costs were covered.

Lecturers supported from NAVI funds were:

1.	Karlheiz Langanke (GSI & TU Darmstadt)	7 days	525 euro
2.	Roland Diehl (MPI Garching)	3 days	225 euro
3.	Thomas Aumann	3 days	225 euro

A number of 6 students were covered:

1.	Sofia Antic (TU Darmstadt)	13 days	750 euro
2.	Mathias Holl (TU Darmstadt)	13 days	750 euro
3.	Andrea Horvath (TU Darmstadt)	6 days	450 euro
4.	Fabia Schindler (TU Darmstadt)	6 days	450 euro
5.	Francois Aymard (Uni de Caen)	13 days	750 euro
6.	Aleksandra Cvetinovic (JSI Ljubljana)	13 days	750 euro

Total: 4875 euro

Other expenses: 125 euro

Grand total: 5000 euro

We attach the epitome of the two weeks of the school. Six receipts signed by the above 6 students are attached, scanned, or in original (if requested). All the above students have presented communications at the school/conference.
The logos of sponsors were prominently displayed during the event and the students supported were advised to acknowledge their sponsor in the papers submitted for the volume of the Proceedings.

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CSSP14 Financial Director

IFIN-

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Carpathian Summer School of Physics 2014

Exotic Nuclei and Nuclear/Particle Astrophysics (V)
"From nuclei to stars"
July 13 - 26, 2014, Sinaia, Romania

Raport catre Ministerul Educatiei Nationale
Comisia pentru manifestari stiintifice si expozitionale

Manifestarea stiintifica: ***Carpathian Summer School of Physics 2014 : Exotic Nuclei and Nuclear/Particle Astrophysics (V). "From Nuclei to Stars"***
Contract MEN nr**. 41M/10.06.2014**

In perioada 13-26 iulie 2014 s-a desfasurat la Sinaia manifestarea stiintifica internationala cu titlul de mai sus (pes curt CSSP14). A fost cea de-a 26-a editie a scolilor de vara de fizica organizate de catre IFA sau IFIN-HH in Carpati si a 5-a din seria cu titlul *Exotic Nuclei and Nuclear/Particle Astrophysics. "From Nuclei to Stars"*. A fost o editie jubilara: se implinesc 50 de ani de la desfasurarea primei scoli de fizica organizata de IFA in vara anului 1964. CSSP14 a fost gazduita in centrul de conferinte al hotelului "International" sin Sinaia, str. Avram Iancu nr. 1, unde au fost cazati si cei mai multi dintre participanti.
Manifestarea a fost organizata de un Comitet de Organizare de la IFIN-HH Bucuresti-Magurele si Cyclotron Institute, Texas A&M University, College Station, TX, SUA, conduis de co-directorii L. Trache (IFIN-HH) si R.E. Tribble (Texas A&M). Este parte din European Network of Nuclear Astrophysics Schools (ENNAS) (impreuna cu alte doua scoli de prestigiu in domeniu: St. Tecla, Catania, Italia si Russbach, Austria). Ea a fost sprijinita financiar de un grant de la MEN (7500 lei) si de catre sponsori internationali: proiectul European ENSAR, network ATHENA (10 mii euro), Nuclear Astrophysics Virtual Institute (NAVI) Germania (5 mii euro), iGroup (1500 euro), Canberra (1600 euro) si CAEN (1000 euro). Manifestarea este recunoscuta de catre European physics Society (EPS). Logo-urile sponsorilor la sfarsitul acestui document.

La eveniment, care a avut prin traditie un format mixt de scoala (in special in prima saptamana) si conferinta, au fost circa 120 participanti:

- 59 de lectori invitati au prezentat 65 de lectii de o ora fiecare
- 55 de studenti care au prezentat un total de 31 de comunicari orale de 20 minute fiecare.

In cadrul scolii doua zile (17-18 iulie) au fost rezervate pt. Conferinta Internationala "ELI-NP. Status and Perspectives". Sambata 19 iulie a avut loc sesiunea traditionala outreach cu tema "CERN @ 60 and the internationalization of science" care a fost onorata de prezenta prof. Rolf Heuer, director general al CERN, prof. T. Prisecaru, secretar de stat MEN, alte persoane din mediul academic romanesc, public si reprezentanti media.

Proceedingsul CSSP14 va fi publicat in prestigioasa serie "AIP Conference Proceedings" a American Institute of Physics, NY in care au fost publicate cele ale ultimelor 3 editii ale scolii.

Comitetul de Organizare al CSSP14 a acordat burse de participare unui numar de 22 studenti, din care 21 din afara tarii. Selectia s-a facut in urma aplicatiilor studentilor care au inclus recomandarile

profesorilor lor, conducatori de doctorat sau de proiect. Aplicatiile au fost acceptate pana la 15 aprilie 2014, iar rezultatele selectiei au fost prezentate pe website la inceputul lunii mai.
Cea mai mare parte a participantilor, atat lectori, cat si studenti, au fost suportati financiar de catre propriile institutii.
Incepand cu 17 iulie s-a deschis in cadrul scolii expozitiile: Scolile carpatine de fizica la 50 de ani, ELI-NP si CERN 60. In cadrul manifestarii, pe durata 17-20 iulie au fost prezenti si un numar de trei expozanti de la cei 3 sponsori economici: iGroup, Canberra si CAEN.

CSSP14 a fost apreciata de toti participantii ca un success deosebit, atat din punct de vedere stiintific, al calitatii lectorilor si lectiilor, a numarului de studenti participanti, cat si organizatoric.

- A fost facuta recomandarea ca scolile sa continue, urmatoarea editie fiind planuita pentru vara anului 2016.
- Sa se continue afilierea la ENNAS, ca si eforturile de a obtine o finantarea initiala prin programul ENSAR2
- In anii viitori vor fi organizate scoli de vara dedicatea ELI-NP si ELI.

Raport financiar integrat:

- Cheltuieli totale: 234.060 lei
    - Din care fonduri beneficiar: 99.877 lei
    - Sponsorizari: 83.941 lei
    - Finantare acordata MEN, contract M41: 7.500 lei
        - Din care chirie sala: 7.500 lei
    - Contributii participant: 42.742 lei

Suma acordata de MEN scolii a fost folosita exclusiv pentru plata partiala a costurilor de inchiriere a saliilor unde s-a desfasurat manifestarea.
Nu sunt incluse sumele cheltuite de participanti pentru cazare, daca au folosit fonduri proprii.
Atasam documentele financiare relevante.

Deasemeni atasam:

- lista participantilor, inclusiv adresele lor
- fisa sintetica a manifestarii
- nota de fundamentare
- epitomul programului conferintei
- copie a programului sesiunii speciale din 19 iulie
- copie a Raportului catre ENSAR ATHENA
- copie a Raportului catre NAVI

Dr. Livius Trache
Director CSSP14
Responsabil contract MEN
Nr. 41M

Ec. Sanda Olteanu
Director financiar CSSP14

Investigating $^{13}C+^{12}C$ Reaction by the Activation Method. Sensitivity Tests

D. Chesneanu[a)], L. Trache, R. Margineanu, A. Pantelica, D. Ghita, M. Straticiuc,

I. Burducea, A.M. Blebea-Apostu, C.M. Gomoiu

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X. Tang

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Abstract. We have performed experiments to check the limits of sensitivity of the activation method using the new 3 MV Tandetron accelerator and the low and ultra-low background laboratories of the "Horia Hulubei" National Institute of Physics and Nuclear Engineering (IFIN-HH). We have used the $^{12}C+^{13}C$ reaction at beam energies E_{lab}= 6, 7 and 8 MeV. The knowledge of this fusion cross section at deep sub-barrier energies is of interest for astrophysical applications, as it provides an upper limit for the fusion cross section of $^{12}C+^{12}C$ over a wide energy range. A ^{13}C beam with intensities 0.5-2 particleμA was provided by the accelerator and used to bombard graphite targets, resulting in activation with ^{24}Na from the $^{12}C(^{13}C,p)$ reaction. The 1369 and 2754 keV gamma-rays from ^{24}Na de-activation were clearly observed in the spectra obtained in two different laboratories used for measurements at low and ultralow background: one at the surface and one located underground in the Unirea salt mine from Slanic Prahova, Romania. In the underground laboratory, for E_{lab} = 6 MeV we have measured an activity of 0.085 ± 0.011 Bq, corresponding to cross sections of 1-3 nb. This demonstrates that it is possible to measure ^{12}C targets irradiated at lower energies for at least 10 times lower cross sections than before. $\beta-\gamma$ coincidences will lead us another factor of 10 lower, proving that this installations can be successfully used for nuclear astrophysics measurements.

INTRODUCTION

With the final goal of establishing a solid line of research in nuclear astrophysics (NA) at the Bucharest accelerators and laboratories of IFIN-HH, we have performed experiments to check the limits of one method that seems appropriate and for which the institute has or could acquire installations: the activation method. We used for irradiation one of the new tandem accelerators which can provide good intensities for light ions and the low and ultralow background laboratories, situated above ground and underground, respectively, for activation measurements. We have chosen the $^{13}C+^{12}C$ reaction, which leads to an activation appropriate for our tests: ^{24}Na, with a half-life of 15.0 hours, formed by one proton evaporation.

Nuclear astrophysics, or more precisely nuclear physics for astrophysics, is becoming more and more an explicit motivation for nuclear physics research, for European laboratories programs, in the USA, Japan and China, but also for the ones from Romania: through direct measurements (at low energies as in stars) or indirect methods (at the most common energies in nuclear physics laboratories). Direct measurements are very difficult because of the low cross sections involved and require dedicated facilities: proton or alpha particle accelerators of very high intensities at low energies and, if possible, low background and special detection systems. Such a facility did not exist in Romania and therefore, direct measurements were not made in Romania. The use of indirect methods involve typically radioactive beams, which were also not available locally. We wanted to prove that we can do direct measurements now, using newly available installations [1,2].

The reaction $^{12}C + ^{12}C$ in the low energy region is of great interest in astrophysics (see eg [3].) because of its essential role in studying a wide range of burning scenarios in carbon-rich stellar environments. It is important for understanding carbon burning nucleosynthesis that occurs in stars with more than 10 solar masses during late evolutionary periods [4], in intermediate mass stars (8-10 solar masses), which can lead a detonation wave and a supernova explosion [5], in binary systems, where a massive carbon-oxygen white dwarf exceeds the Chandrasekhar mass limit accumulating material from its partner star. The temperatures at which the carbon burnout occurs are found in the range of 0.5-1.2 GK corresponding to the center-of-mass energy range of 1 to 3 MeV. To verify all these scenarios and put constraints on models requires a detailed knowledge of the carbon fusion processes at these energies. Considerable efforts have been made to measure the cross section of $^{12}C + ^{12}C$ reaction at astrophysical energies, involving both the detection of charged particles and gamma-ray spectroscopy. However, previous measurements were made for $E_{c.m} \geq 2.1$ MeV, the upper region of astrophysical interest. Also, as $E_{c.m} = 3.0$ MeV cross sections reported are not consistent and are quite uncertain [6-8]. Moreover, the extrapolation procedure in the case of $^{12}C + ^{12}C$ from current experimental data at ultra-low energies is complicated by the presence of possible resonant structures even in the low energy excitation function. Measurements that could extend to below $E_{c.m} = 2.1$ MeV would be extremely important. It was found, however, that the $^{13}C + ^{12}C$ and $^{13}C + ^{13}C$ reactions do not have such resonances and provide material for understanding fusion at low energies, and ways to determine the maximum cross section for the reaction $^{12}C + ^{12}C$.

A University of Notre Dame group [9] has proposed a $^{13}C + ^{12}C$ experiment in collaboration with us and a group of Lanzhou, China at 3 MV Tandem from IFIN-HH. It is the motivation for our choice of measurements here: irradiations with a ^{13}C beam followed by measurement of activities at both surface and underground laboratory characterized by an ultra-low background radiation.

EXPERIMENTAL METHODS FOR INVESTIGATION OF THE $^{12}C + ^{13}C$ REACTION BY THE ACTIVATION METHOD

The *HVEE Tandetron 3 MV electrostatic accelerator* - recently installed at IFIN-HH is dedicated to:

1) Ion Beam Analysis (IBA) - analytical techniques that use accelerated ion beams: Rutherford backscattering spectrometry (RBS), X-ray emission induced by charged particles (PIXE), nuclear reaction analysis (NRA), etc.

2) Testing the radiation resistance of the materials or implants.

3) Nuclear astrophysics.

For nuclear astrophysics we assess that this facility is suitable for direct measurements of cross sections induced by α particles (He-burning) and light ions (^{6}Li, ^{12}C, ^{13}C, ^{16}O ...), due to relatively low energies and high intensities and its stable functioning, as tested by us last year.

The *GammaSpec laboratory* is an above ground installation in IFIN-HH main campus, in the same location as the tandem accelerators, consisting of a HpGe detector very well shielded, and carefully calibrated with sources and international inter-laboratory comparisons [10, 11].

The *Underground Laboratory in the Unirea salt mine, Slanic Prahova (MicroBequerel or "μBq")*, is located in a salt mine, about 2 hours drive North of Bucharest. Environmental conditions in the salt mine are very stable year round: temperature between 12 and 13^{o} C, humidity 67-70% approximately, area of ~70,000 m^2, height between 52 and 57 m, depth is 208 m below ground (approximately 600 m.w.e), the distance between the walls is between 32 and 36 m, volume is 2.9×10^{6} m^3 [12]. In this mine a laboratory was built to perform measurements using gamma-ray spectrometry in ultralow radiation background. The average dose underground was found 1.29 ± 0.30 nSv/h, approximately 70-80 times lower than the dose at the surface. As ambient background radiation comes from: i) natural radioactivity (especially from the decay of ^{238}U, ^{232}Th and ^{222}Rn present in the atmosphere and ^{40}K); ii) cosmic rays (μ, ^{1}H, ^{3}H; ^{7}Be, ^{14}C ...); and iii) neutrons from (α, n) reactions and fission, the i) and iii) sources are particularly low in this mine due to its thick and compact salt walls. Figure 1 compares γ-ray spectra measured above ground and underground. The top spectrum shows that the strongest component of the γ rays spectrum at E_γ<3MeV is associated with the natural environment radioactivity and exhibits intense characteristic lines. At higher energies, the background radiation originates mostly from cosmic rays. The natural radioactivity is significantly reduced for measurements in the underground laboratory (bottom spectrum). From Fig. 1 it can be seen that the measured background radiation (using a protection shield consisting of 15 cm Pb and 5 cm Cu produced by Canberra Ind.) is about 4000 times smaller compared to the background spectrum measured at the surface. This is the major advantage we want to test and use in the current measurements [13, 14].

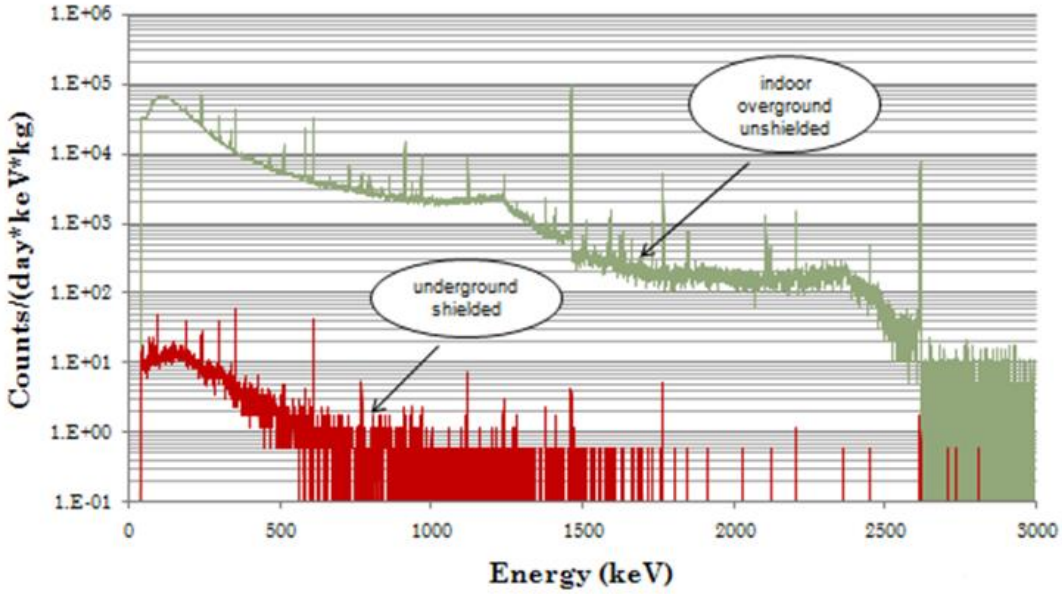

FIGURE 1. Typical spectrum of γ rays measured at the Earth's surface and underground

EXPERIMENTAL RESULTS

In this experimental phase we studied ^{12}C + ^{13}C fusion reaction in the laboratory energy range of 6 to 8 MeV. A $^{13}C^{+3}$ beam with intensity 0.5 μA, at the first irradiation (E_{lab}=8 MeV), and 1.9 μA, for the irradiations at energies E_{lab}= 6 and 7 MeV, provided by the 3 MV Tandetron accelerator, impinged on a 1 mm thick natural carbon (graphite) target. A gas stripper system was used to increase the intensity of the $^{13}C^{+3}$ charge state.

Cross section of the $^{12}C(^{13}C, p)$ ^{24}Na reaction can be determined by measuring the γ radiation corresponding to nucleus ^{24}Na ($T_{1/2}$ = 15.00 h), using the activation method. The irradiated carbon targets were measured in the GammaSpec laboratory and in the underground laboratory. The cascading γ rays (1369 and 2754 keV) were detected with germanium detectors. The detection systems have been protected with lead castles to reduce ambient background radiation. The first case studied was a C target irradiated for 15 hours with an 8 MeV beam. γ rays were measured in the underground laboratory 4 times successively, 82.000 s each measurement (comparable to $T_{1/2}$ of ^{24}Na) using a germanium detector with 120% relative efficiency, in a protective castle as described before. We found an activity of 4.44 ± 0.19 Bq and evaluated the minimal detectable activity at 0.048 Bq. In the four the γ-ray spectra we could observe the decreasing activity of the irradiated target and the gradual relative increase of the background radiation.

The following two steps consisted of the activation of C targets at two different beam energies, 6 and 7 MeV, and from measuring them both in the underground laboratory and in the GammaSpec laboratory located at the surface. In this latter laboratory, the spectrometric system is based on an Ortec HPGe detector 30185 GEM, resolution 2.1 keV at 1332 keV of ^{60}Co, and relative efficiency 30% (compared to 3 "x 3" NaI (Tl) standard). This spectrometric system is protected by a lead cylindrical shield (10 cm thick), covered on the inside with tin (1 mm thick) and copper (1.5 mm thick) foils. Thus for γ rays of energies between 20 and 2750 keV in a 24 hours measurement one obtains a count rate of 1.2-1.8 events/sec (depends mainly on the concentration of ^{222}Rn in natural background).

For the target irradiated (23 hours) at E_{lab} = 7 MeV, and measured in the GammaSpec laboratory, the beam intensity was 1.87 μA, yielding an activity at the end of irradiation equal with 5.20 ± 0.40 Bq. This activity was calculated after corrections were made for the efficiency and the time needed to transport the target from the reaction chamber to the GammaSpec laboratory. For measurements made in the underground laboratory another C target was irradiated using the same parameters, but for a longer irradiation time of about 25 hours.

Activity values measured in the two laboratories are shown in Tables 1 and 2; the two sets of measurements gave comparable results, within the evaluated uncertainties. The incident ^{13}C beam energy (E_{lab}) in MeV, beam current (I) in μA, and counting time of the irradiated targets (t_c) in seconds are also given in these tables. Knowing the activated targets activity at the measurement moment and the background rate of accumulation we determined the limit of detection for the evaluation of the $^{12}C + ^{13}C$ fusion reaction cross sections. The minimum measurable cross section results to be about 3 nb using beam intensity around 0.6 pμA (particleμA, $^{13}C^{+3}$ charge state) , as in these cases. That is an order of magnitude below the lowest value measured until now in other laboratories. Increasing the beam intensity to approximately 6-10 pμA, it is possible to decrease the limit of detection of 10 more times, so we can measure at the energies lower than those now existing in the literature.

Tests conducted at the lowest $E_{lab}(^{13}C)$ = 6 MeV have revealed low activities of the activated targets, but to which the experimental setups are still sensitive. Barely in the surface lab, but clearly in the underground one (see Fig. 2) [15]. Reducing the limit by an order of magnitude is still possible by increasing the beam intensity. There will be, however, limitations on the extent to which the current intensity can be increased without damaging the targets. A high current beam raises problems with sputtering effect (some produced ^{24}Na's are sputtered away from the target surface during irradiation) and with heating effects. In a test at 10 μA we had visible signs of carbon sputtering from the target. For future measurements it will be necessary to construct a target cooling system. But again there is a limitation on how heat can be dissipated in the target.

Another way to improve the signal-to-noise ratio in de-activation measurements is using the β–γ coincidence method. This method allows to suppress the ambient background γ rays from natural radioactive isotopes such as ^{40}K and ^{208}Tl. In the Notre Dame experiment the peaks at 1369 keV and 2754 keV of ^{24}Na could be observed only in the β gated γ-ray spectra. It is obvious that this experimental setup made now at IFIN-HH, will allow decreasing the total fusion cross section from this measurement with another order of magnitude.

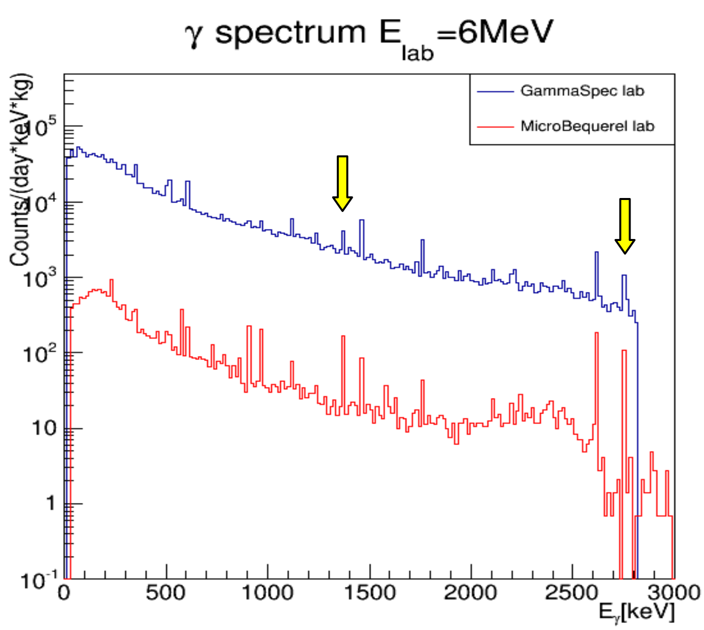

FIGURE 2. Comparison between γ spectra (E_{lab} = 6 MeV) measured in underground laboratory and GammaSpec laboratory (arrows-the cascading γ rays 1369 and 2754 keV)

TABLE 1. Experimental results obtained in GammaSpec laboratory

$E_{lab}(^{13}C)$ (MeV)	I(μA)	t_c(s)	^{24}Na (Bq)
7.0	**1.87**	**81000**	**5.20 ± 0.40**
6.0	**1.90**	**86400**	**0.115 ± 0.018**

TABLE 2. Experimental results obtained in the underground laboratory

$E_{lab}(^{13}C)$ (MeV)	I(μA)	t_c(s)	^{24}Na (Bq)
7.0	**1.87**	**86400**	**5.23 ± 0.043**
6.0	**1.90**	**84480**	**0.085 ± 0.011**

CONCLUSIONS

Study of carbon burning is an open question in nuclear astrophysics. This process represents the third stage of stellar evolution of massive stars with mass greater than 8 stellar masses that continue mainly through $^{12}C + {}^{12}C$ fusion processes and to a lesser extent by $^{12}C + {}^{16}O$. Direct measurement at the Gamow window energies are therefore essential, but are difficult to carry due to the background from the cosmic rays, terrestrial environment and/or accelerator beams. Major improvements can be achieved by using high intensity accelerators, advanced detection techniques and/or underground measurements. $^{12}C + {}^{13}C$ fusion process gives information about the fusion mechanism at low energies and can be studied both in-beam γ spectroscopy and activation method using experimental setups that consists of an accelerator and detectors for γ spectroscopy.

To determine the optimum parameters of this experiment, stability and resolution tests of ^{12}C beam obtained at the 3 MV accelerator of IFIN-HH were conducted last year. Following these tests, it turns out that the accelerator has the characteristics required for nuclear astrophysics measurements, namely: allow the terminal voltage between 0.1-3.2 MV, stable while providing stability of incident beam energy used, the currents are stable over time, allowing precise measurements. In particular, the intensities of the order of 10 pμA obtained for ^{12}C, an order of magnitude higher than those obtained from the University of Notre Dame FN tandem, make possible to carry the proposed experiments in collaboration with the group from there.

We studied the $^{12}C+{}^{13}C$ fusion reaction in the energy range $E_{c.m}$ = 2.9 - 3.8 MeV using the activation method and gamma-ray spectroscopy. Activities of irradiated targets measured both in the underground and surface laboratories allowed to determine the limit of detection of cross sections of the order of 1-3 nb. By increasing the intensity it is possible to gain a factor of 10 in sensitivity and by using β–γ coincidences, another factor of 10. However, this will imply a good cooling of the graphite targets. We emphasize that the minimum value of the measurable cross sections in general, is dependent on the specific characteristics of the produced isotope and of the γ transition(s) used, but the order of magnitude set here (nanobarns) remains valid, as remains the possibility to reduce it by increasing the intensity and using β–γ coincidences. Calibrations and measurements performed in identical or similar conditions will also allow us to reduce the uncertainties associated with the experimental data corresponding with range $E_{c.m}$ =

2.6-5.0 MeV below 20%, and to determine the cross section for the ^{12}C + ^{13}C process at an energy lower than $E_{c.m}$ = 2.6 MeV.

In conclusion, the 3 MV accelerator is suitable for nuclear astrophysics measurements due to energies and intensities provided and stability in operation. Low (DFN) and ultralow ("μBq" Slanic) background laboratories of the institute can be successfully used for measurements by activation with lifetime greater than ten minutes and several hours, respectively, necessary to transport the probes. These facilities have been included recently in a European project proposal Horizon 2020 program, called the European Laboratory Astrophysics Network (ELAN) as TA (Transnational Access facility), in a select group of seven multi-disciplinary laboratories of atomic and molecular spectroscopy or radiation installations and of only two other nuclear astrophysics labs.

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