Project: PNIII-P4-ID-PCE-2016-0743

Project title: "Direct measurements of Nuclear Astrophysics at IFIN-HH"
NUCASTRO2
Intermediate Report January – December 2019

Etapa 3 - 2019: Measurements of reactions induced by light ions at energies relevant in nuclear astrophysics

Masuratori de reactii cu ioni usori la energii relevante pentru astrofizica nucleara

1. Introduction

This is the intermediary report for the period Jan. – Dec. 2019.

There were no changes in the personnel since the last report, in Dec. 2018.

The focus of the Nuclear Astrophysics Group (NAG) at the Department of Nuclear Physics (DFN) from IFIN-HH is **nuclear physics for astrophysics**. While the group is using also indirect methods using radioactive beams at international facilities, the use of **direct** measurements **for nuclear astrophysics** is mostly funded through this project. As a rule, the activities in the group were coherently focused in the research area of nuclear astrophysics and were financed by this project and its sister project NAIRIB of IFA FAIR-RO program, as well as with funds from other sources, national (PN) and international (COST or ENSAR2), and the results cannot always be disentangled.

The present report includes and supplements the intermediary report for 2019 sent in September.

NAG continued to work in 2019 in nuclear physics for astrophysics (NPA) **research** and **education and formation.** These two activities separated only in form but interlaced in reality will be detailed briefly below.

2. Research

The research could be split in several distinct activities.

The start of a program to study ion-ion fusion reactions at energies relevant for nuclear astrophysics.

In the assembly of known stellar nuclear processes that are the source of both stellar energy and production of chemical elements, many of the important reactions are those of capture of very light particles: protons, neutrons and alphas. There are, however, a few crucial or very important reactions between light ions heavier than ^{4}He ("metals" in the jargon of nucleosynthesis). Among them those involving ^{12}C and ^{16}O: ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O. Even at the very high stellar temperatures occurring in explosive burning of massive stars, reaching a few GK, these reactions happen at very low energies, well below the Coulomb barriers. This makes them difficult to study experimentally. However, many attempts were and are being made, either through indirect methods or by direct measurements at energies as low as possible. Part of these are the **attempts to understand the fusion reaction mechanisms at such energies, testing models that would guide the extrapolations toward the energies in the**

Gamow window. **We intend to extend in this direction** a few studies that we have done so far in the area.

For example, ^{12}C+^{12}C is a reaction of critical importance in nucleosynthesis. Carbon burning influences the fate of massive stars and super-bursts from accreting neutron stars. There is a rich literature of attempts to measure or evaluate the fusion cross section at low energies, which turns out to be dominated by resonances. Most of the direct measurements stop above the Gamow window, unable to go lower due to the very low cross-sections (see [2] and references therein).

However, using various indirect methods, it was possible for the reaction to be studied at energies below the barrier. A spectacular and important measurement was done using the Trojan Horse Method (THM), a project that started with experiments in Bucharest and continued at LNS Catania, in which I was involved and was published in the journal Nature [1]. Our nuclear astrophysics group (NAG) at IFIN-HH has also measured this reaction indirectly, using the adjacent ^{13}C+^{12}C reaction to evaluate the reaction mechanisms at sub-barrier energies. This was a substantial joint effort with a group from IMP Lanzhou, China, with experiments conducted at the 3 MV Tandetron^{TM} of IFIN-HH (irradiations) and activity measurements in our ultra-low background laboratory in the Slanic-Prahova salt mine. The very low gamma-ray background in the mine was a critical factor in reaching down to energies corresponding to the Gamow window. We were able to use this particular method due to the fact that one of the fusion-evaporation channels lead to the production of unstable ^{24}Na, with a half-life ($T_{1/2}$ = 15.0 h) that permitted the transfer of the samples to the salt mine without considerable loss of activity. This work has been completed and submitted for publication [3]. Figure 1 shows that our work was successful in selecting from the fusion models proposed in the literature and contradicts a very popular hindrance model of recent years [2,4].

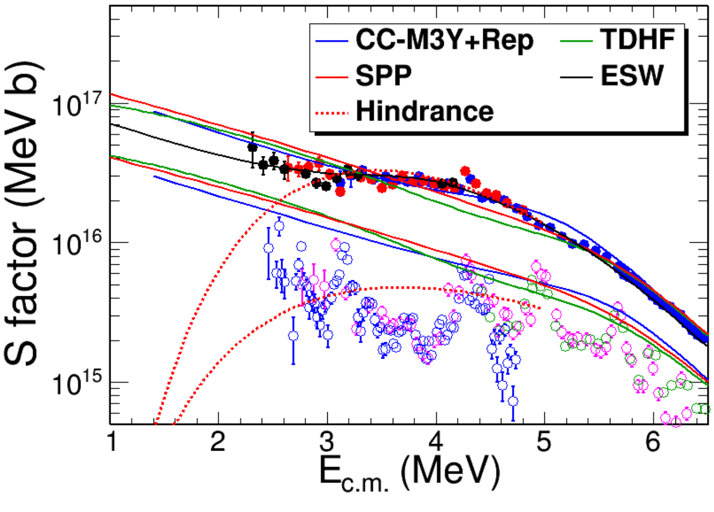

Figure 1. *S-factor vs E plot for the adjacent systems,* ^{12}C+^{12}C *and* ^{13}C+^{12}C*. The solid circles represent experimental data for the* ^{13}C+^{12}C *reaction. The empty circles correspond to experimental measurements for the* ^{12}C+^{12}C*. The various lines represent theoretical calculations with the different models indicated in the plot legend [3]. There is an artificial factor of 10 reduction for the* ^{12}C+^{12}C *to make points and curves distinguishable.*

As such, we planned a program to study ion-ion fusion reactions at very low energies, motivated by nuclear astrophysics. The most important in this category are the reactions between ^{12}C and ^{16}O nuclei. We studied ion-ion fusion reactions in various ways. The start was with the most important in the list: ^{12}C+^{12}C, described above: the study using the Trojan Horse Method (THM), and the study of the fusion of nuclides adjacent in the nuclide chart: ^{13}C+^{12}C. The study was carried out experimentally in IFIN-HH, using our 3 MV accelerator and the ultra-low background micro-Bequerel laboratory we have in the Slanic-Prahova salt mine. We were using two totally different methods, in collaboration with prestigious groups from abroad. Our program to study the **fusion reaction mechanisms at sub-Coulomb energies** started with the following steps:

- We proposed to the PAC of IFIN-HH tandems at its Nov. 2018 session a ^{17}O+^{12}C experiment at the 3 MV tandetron.

  "Test of ion-ion fusion mechanisms at sub-barrier energies for nuclear astrophysics. *Proposal submitted for the Nov. 2018 IFIN-HH PAC session by*: Alexandra Spiridon, Dana Tudor, Alexandra Chilug, Ionut Stefanescu, Iuliana Stanciu, Mihai Straticiuc, Ion Burducea, Livius Trache, *IFIN-HH, Bucharest-Magurele, Romania"*

  In-beam gamma-ray and de-activation measurements will be carried out. The proposal was accepted with maximum priority.
- We worked for the preparation of this experiment. It was expensive and impractical to obtain in time enriched ^{17}O to put in the accelerator's source. We searched for a solution to have an oxygen target and a ^{13}C projectile. We found that a good solution may be to use Cerium Oxide CeO_2 targets. These were produced in DFN's target laboratory.
- We had a first test experiment in June 2019. We needed to use the beta-gamma coincidence utility BEGA that we developed last year, as the activities produced do not have a sufficiently long lifetime to be transferred to Slanic. A new test was done in one 3 days run in Sept. 2019. We tested how we can measure short lifetimes activities. Work continues on this subject.
- A new proposal on this subject was submitted to the PAC of IFIN-HH tandems for its session of Nov. 2019, with two other reactions proposed.

In the same extended program to study ion-ion reactions relevant for nuclear astrophysics, very recently, Oct. 2019, we participated at the experiment NitrOx at LNS Catania. It attempts to study the reaction ^{12}C+^{16}O using the Trojan Horse Method. This is obviously the continuation of the study of the ^{12}C+^{12}C reaction, which was successfully completed by the publication [1] in 2018. While there are preliminary signs that we had a good experiment, the data analysis is far from being completed.

Completion of interpretation of data from past experiments and the preparation of papers for publication in 2019.

Several of the past activities reached the point where we had to publish the results.
Among those related strictly to the present grant, we finalized and submitted for publication:

A paper was completed and submitted for publication:
A facility for direct measurements for nuclear astrophysics at IFIN-HH -- a 3 MV tandem accelerator and an ultra-low background laboratory.
Authors: D. Tudor, L. Trache, Alexandra I. Chilug, Ionut C. Stefanescu, Alexandra Spiridon, Mihai Straticiuc, Ion Burducea, Ana Pantelica, Romulus Margineanu, Dan G. Ghita, Doru G. Pacesila, Radu F. Andrei, Claudia Gomoiu, Ning T. Zhang, Xiao D. Tang.

It was submitted to Nucl. Instr. & Meth. A, June 26, 2019. The reviewers found that " … this work is suitable for publication … is something original and scientifically competitive" (in the words of Ref. 1) and "has a bunch of information inside that is useful and should be published as an overview describing a new experimental facility and opportunity for the Eastern European community" (in the words of Ref. 2), and asked for a few revisions, which we made and resubmitted on Sep. 24, 2019. It was also posted on arXiv: http://arxiv.org/abs/1907.03596. The paper was published online on Dec. 4, 2019 as Nuclear Inst. and Methods in Physics Research, A 953 (2020) 163178 at
https://authors.elsevier.com/a/1aAYccPqbao9v
It is appended to this report.

The paper:
Constraining the 12C+12C astrophysical S-factors with the 12C+13C measurements at very low energies
By N. T. Zhang, X. Y. Wang, H. Chen, Z. J. Chen, W. P. Lin, W. Y. Xin, S. W. Xu, D. Tudor, A. I. Chilug, I. C. Stefanescu, M. Straticiuc, I. Burducea, D. G. Ghita, R. Margineanu, C. Gomoiu, A. Pantelica, D. Chesneanu, L. Trache, X. D. Tang, B. Bucher, L. R. Gasques, K. Hagino, S. Kubono, Y. J. Li, C. J. Lin , et al.
This paper was written before, but not published. We reviewed it and changed some of its conclusions to co-ordinate with the *Nature* publication I mentioned above [1]. It was submitted to Phys. Lett. B on Sept. 2, 2019. It is posted at: arXiv:1909.07012.

We can safely say that these latter two papers summarize best the activity under this NUCASTRO2 project:

- A facility for direct measurements in nuclear astrophysics at IFIN-HH was setup and fully confirmed. The experimental procedures for the irradiation of samples at the accelerator, and the subsequent de-activation measurements in an ultra-low background laboratory, as well as their calibration and characterization, the determination and the proof of its international viability and competitivity are complete.
- A case of an important reaction was measured completely, with a sensitivity 100 higher than any before and with demonstrated consequences for nuclear astrophysics.
- Additionally, they opened a new program of studies of ion-ion fusion at sub-Coulomb energies. That started with the realization of the BEGA coincidence system in 2018 and with the reactions we started to measure in 2019.

In June this year I presented an invited lecture at the10th European Summer School on Nuclear Astrophysics, June 16-23, 2019, Catania, Italy with the title *"Nuclear Astrophysics Studies at NIPNE"*. In September I finalized the paper for the Proceedings of that event, paper that was accepted by the referees and will be published in Eur. Phys. J. Conf. Series. I append this to the present report.

Proceedings of the Carpathian Summer School of Physics 2018

The 28th edition of the Carpathian Summer School of Physics took place in July 2018, in Sinaia, as described in our Dec. 2018 report. Editors' work to publish the proceedings was finalized at the beginning of 2019 and the volume was published, first online, then in print, in March-April 2019. The reference for it is:

Livius Trache and Alexandra Spiridon (eds.), *Exotic nuclei and nuclear/particle astrophysics (vii) - Physics with small accelerators. Proceedings of the Carpathian Summer School of Physics 2018 (CSSP18).* Book Series: American Institute of Physics Conference Proceedings, Volume: 2076, Melville, New York, 2019.
https://aip.scitation.org/toc/apc/2076/1?expanded=2076

I should mention here, though, that I was not allowed to use institute funds (that we've obtained from outside sources that I dully indicated) to pay for the printed copies that were sent to the participants, as per the announcements that we made when we launched the event. Fortunately, I could obtain the understanding and approval of colleagues from the H2020 project ENSAR2, and the NUSPRASEN networking activity has paid the $6,800 due to the American Institute of Physics, the publishing house of the volume. I stress that this amount was not for the publication of the volume but represented the cost of the printing and distribution of individual copies to each of the participants to the event.

3. Education and formation

The education and formation of younger researchers continued to be the focus of the group and of the project director. Briefly:

- The younger members of the group were consistently advised and prepared to participate to international events on nuclear astrophysics. In addition to funds from this grant and from the grant NAIRIB (PN III-P5-P5.2-2016), we could use European funds from the COST action CA16117 ChETEC for five such participations. In each one of these cases they were presenting communications.
- Three of the four PhD students have thesis subjects related to experiments at prestigious international laboratories in Japan, USA and Germany. They all travelled there for work. In two cases, the host laboratories have supported the costs, a sign of appreciation of their contributions. All three have obtained stipends for longer periods of time at RIKEN, Japan (A. Chilug and I. Stefanescu) and Technische Universitaet Muenchen (I. Stanciu), respectively.
- The fifth edition of the (national) Summer School for Physics Olympics, July 16-23, 2019 was organized again in Busteni in collaboration with the NGO Apex-Edu from Cluj-Napoca. This edition of the event was well appreciated by the about 20 high school students, best in their senior classes, selected from the finalists of the Romanian Physics Olympiads. In addition to the PD who is the director of the scientific part of these schools, two young members of NAG were lecturing in Busteni. Dr. Alexandra Spiridon was talking about her experience as PhD student in USA, while drd. Alexandra Chilug was talking about her thesis work in IFIN-HH, centred on an experiment we had at RIBF RIKEN in Wako, Japan.
- At this section on formation of the new generations of scientists I should include that one group member has proposed (Oct. 2019) a project in the new UEFISCDI competition for Post-Doctoral grants on the study of ion-ion fusion mechanism and that the NAG youngsters have 4 local beamtime proposals approved by PAC and one external proposal accepted at Texas A&M University (to be run Nov. 25 – Dec. 5, 2019).

At this same chapter the proposals for future events in which the PD and NAG are the main organizers should be included:

- A proposal of a new edition of a training school "hands-on experiment in nuclear astrophysics at IFIN-HH" was approved the recent (Sep 18, 2019) meeting of ChETEC Management Committee for April 2020. The event will be fully financed by COST.
- Accordingly, a beamtime proposal was submitted to the PAC of Nov. 2019. The experiment was approved with maximum priority: 7 days of beamtime at the 3 MV tandetron.
- An ECT* workshop "Key Reactions in Nuclear Astrophysics" (the PD as co-organizer) was submitted and was approved by the ETC* scientific board for June 22-26, 2020. The workshop is organized by the same group of 5 scientists from 5 countries and 3 continents that have successfully organized the ECT* workshop of Nov. 2018 (see the 2018 report).

[1] A. Tumino, … and L. Trache, *Nature*, vol. **557**, 687 92018).

[2] C. L. Jiang, K. E. Rehm, B. B. Back, and R. V. F. Janssens, **Phys. Rev. C 75**, 015803 (2007).
[3] N. Zhang ... D. Tudor, A.I. Chilug, I.C. Stefanescu, M. Straticiuc, I. Burducea, D.G. Ghita, R. Margineanu, C. Gomoiu, A. Pantelica, D. Chesneanu, and L. Trache, ... **Phys. Lett. B**, 2019, submitted.
[4] C. L. Jiang et al. **Phys. Rev. C 97**, 012801 (2018).

4.1 List of new publications of PD and NAG members (as per ISI Web of Science, Nov. 2019)

1. Burjan, V.; Hons, Z.; Kroha, V.; et al., EUROPEAN PHYSICAL JOURNAL A Volume: 55, Article Number: 114. Published: JUL 23 2019.
The determination of the astrophysical S-factor of the direct O-18(p, gamma)F-19 capture by the ANC method

2. Chilug, A. I.; Panin, V.; Tudor, D.; et al., Group Author(s): HI-p Collaboration
EXOTIC NUCLEI AND NUCLEAR/PARTICLE ASTROPHYSICS (VII) - PHYSICS WITH SMALL ACCELERATORS Book Series: AIP Conference Proceedings, Volume: 2076, Article Number: UNSP 060001. Published: 2019.
Study of the C-9 Breakup Through NP1412-SAMURAI29R1 Experiment

3. Stefanescu, I. C.; Trache, L.; Chilug, A. I.; et al.
EXOTIC NUCLEI AND NUCLEAR/PARTICLE ASTROPHYSICS (VII) - PHYSICS WITH SMALL ACCELERATORS, Book Series: AIP Conference Proceedings, Volume: 2076, Article Number: UNSP 060008. Published: 2019.
Decay Spectroscopy As A Tool For Nuclear Astrophysics

4. Trache, Livius, in EXOTIC NUCLEI AND NUCLEAR/PARTICLE ASTROPHYSICS (VII) - PHYSICS WITH SMALL ACCELERATORS, Book Series: AIP Conference Proceedings, Volume: 2076, Article Number: UNSP 070001. Published: 2019.
The Outreach Sessions

5. Tudor, D.; Chilug, A. I.; Stefanescu, I. C.; et al., in EXOTIC NUCLEI AND NUCLEAR/PARTICLE ASTROPHYSICS (VII) - PHYSICS WITH SMALL ACCELERATORS Book Series: AIP Conference Proceedings Volume: 2076 Article Number: UNSP 060010 Published: 2019.
Experimental study of the alpha+Zn-64 reaction in the Gamow region

6. Gulino, Marisa; Cherubini, Silvio; Rapisarda, Giuseppe Gabriele; et al.
Conference: 9th European Summer School on Experimental Nuclear Astrophysics Location: Catania, ITALY Date: SEP 17-24, 2017. 9TH EUROPEAN SUMMER SCHOOL ON EXPERIMENTAL NUCLEAR ASTROPHYSICS Book Series: EPJ Web of Conferences Volume: 184 Article Number: UNSP 01008 Published: 2018.
Trojan Horse Method experiments with radioactive ion beams

Newer publications

7. A. Spiridon, Emmanuel Pollacco, Antti Saastamoinen, Robert E. Tribble, George Pascovici, Livius Trache, Bertrand Mehl, Rui de Oliveira, Nuclear Inst. and Methods in Physics Research, A **943**, 162461 (2019).
A study in using MICROMEGAS to improve particle identification with the TAMU-MDM focal plane detector

8. D. Tudor, L. Trache, Alexandra I. Chilug, Ionut C. Stefanescu, Alexandra Spiridon, Mihai Straticiuc, Ion Burducea, Ana Pantelica, Romulus Margineanu, Dan G. Ghita, Doru G. Pacesila, Radu F. Andrei, Claudia Gomoiu, Ning T. Zhang, Xiao D. Tang. Nuclear Inst. and Methods in Physics Research, **A 953** (2020) 163178.
A facility for direct measurements for nuclear astrophysics at IFIN-HH -- a 3 MV tandem accelerator and an ultra-low background laboratory

9. https://arXiv:1909.07012
N. T. Zhang, X. Y. Wang, H. Chen, Z. J. Chen, W. P. Lin, W. Y. Xin, S. W. Xu, D. Tudor, A. I. Chilug, I. C. Stefanescu, M. Straticiuc, I. Burducea, D. G. Ghita, R. Margineanu, C. Gomoiu, A. Pantelica, D. Chesneanu, L. Trache, X. D. Tang, B. Bucher, L. R. Gasques, K. Hagino, S. Kubono, Y. J. Li, C. J. Lin , et al. Submitted to Phys. Lett. B, Sep. 2019
Constraining the 12C+12C astrophysical S-factors with the 12C+13C measurements at very low energies

10. A A. Chilug, D. Tudor, A. Spiridon, I. Stefanescu, L. Trache, …et al, in *Proc. Nucleus-Nucleus Collisions 2018, Saitama, Dec. 2018*, Japan Phys. Soc. Conf. Ser., accepted July 2019.

11. L. Stuhl, … A. Chilug, D. Tudor, A. Spiridon, I. Stefanescu, L. Trache, …et al, Nucl. Instr. &Meth. B, accepted 2019, in press.

12. L. Trache, in *Proc. ESSENA 2019*, Eur. Phys. J. Conf. Ser., accepted Sep. 2019.
Nuclear astrophysics studies at NIPNE

13. A. Saastamoinen, E. Pollacco, B.T. Roeder, R. Chyzh, L. Trache, R.E. Tribble, Nucl. Instr. & Meth. B, accepted May 2019, in press.
Studies of systematic effects of the AstroBox2 detector in online conditions

14. A. Tumino, C. Spitaleri, M. La Cognata, S. Cherubini, L. Guardo, M. Gulino, S. Hayakawa, I. Indelicato, L. lamia, H. Petrascu, R.G. Pizzone, S.M.R. Puglia, G.G. Rapisarda, S. Romano, M.L. Serghi, R. Sparta and L. Trache, Il Nuovo Cimento **42** C (2019) 55 *Uncovering carbon burning in stars.*

Books

Livius Trache and **Alexandra Spiridon** (eds.), *Exotic nuclei and nuclear/particle astrophysics (vii) - Physics with small accelerators. Proceedings of the Carpathian Summer School of Physics 2018 (CSSP18).* Book Series: American Institute of Physics Conference Proceedings, Volume: 2076, Melville, New York, 2019.

4.2 Conference participations and presentations Jan. – Dec. 2019

1. L. Trache, 16th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 10-16, 2019. Invited lecture “*Epilogue: the 3 ENNAS schools – past, present and future”*.
2. A. Spiridon, 16th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC.
3. D. Tudor, 16th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC.
4. I. Stefanescu, 16th Russbach Winter school on nuclear astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC
5. L. Trache, European Summer School on Experimental Nuclear Astrophysics 2019, June 16-23, Catania, Italy. Invited talk *Nuclear Astrophysics at IFIN-HH.*
6. A. Spiridon, European Summer School on Experimental Nuclear Astrophysics 2019, June 16-23, Catania, Italy. Communication. Supported by ChETEC
7. L. Trache, ChETEC Management Committee meeting (invited) and Nuclear Physics for Astrophysics IX, Sep. 15-20, 2019, Frankfurt, Germany. Supported by ChETEC.
8. L. Trache, "ChETEC follow-up in Horizon 2020 and Horizon Europe Programmes", workshop in Dresden on November 11-12, 2019.

ChETEC is the COST Action CA16117 “Chemical Elements as Tracers of the Evolution of Cosmos”.

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A facility for direct measurements for nuclear astrophysics at IFIN-HH - a 3 MV tandem accelerator and an ultra-low background laboratory

D. Tudor [a,b], L. Trache [a,*], A.I. Chilug [a,b], I.C. Stefanescu [a,b], A. Spiridon [a], M. Straticiuc [a], I. Burducea [a], A. Pantelica [a], R. Margineanu [a], D.G. Ghita [a], D.G. Pacesila [a], R.F. Andrei [a], C. Gomoiu [a], N.T. Zhang [c], X.D. Tang [c,d]

[a] *Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, IFIN-HH, 077125 Bucureşti-Măgurele, Romania*
[b] *Doctoral School of Physics, University of Bucharest, 077125 Bucureşti-Măgurele, Romania*
[c] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[d] *Joint department for nuclear physics, Lanzhou University and Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

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ABSTRACT

We present a facility for direct measurements at low and very low energies typical for nuclear astrophysics. The facility consists of a small and robust tandem accelerator where irradiations are made and an ultra-low background laboratory located in a salt mine where very low radio-activities can be measured. Both belong to "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), but are situated 120 km apart. Their performances are shown using a few cases where they were used. We argue that this facility is competitive for the study of nuclear reactions induced by alpha particles and by light ions at energies close to or down into the Gamow windows. A good case study was the $^{13}C+^{12}C$ fusion reaction, where the proton evaporation channel leads to an activity with $T_{1/2}$=15 h, appropriate for samples' transfer to the salt mine. Measurements were done using the thick target method down into the Gamow window for energies from $E_{c.m.}$= 2.2 MeV, which is the lowest energy ever reached for this reaction, up to 5.3 MeV, using ^{13}C beams from the 3 MV Tandetron. The activation method allowed us to determine a cross section of the order of 100 pb. Reactions induced by alphas were also measured. Proton induced resonant reactions were used to calibrate the accelerator terminal voltage. Some results of the experiments characterizing the assembly are shown and discussed.

1. Introduction

Nuclear astrophysics (NA) is for some time already an important part of the science program of most nuclear physics laboratories. The experimental studies can be divided as direct measurements – reactions studied at the low energies as they happen in stars, or as close to that as possible, followed by extrapolations into the so called Gamow window – and indirect methods, where information (nuclear data) is extracted from reactions at much larger energies, information that is then used to evaluate the reaction cross sections or the reaction rates in the region of energies relevant for astrophysics. This is due to the fact that at low energies the reactions involving charged particles – and this is a large part of reactions in stellar environments – are very much hindered by the Coulomb barrier, leading to considerable measurement difficulties [1]. Therefore, the case of direct measurements calls for special experimental solutions. One of them is to install high intensity accelerators in underground laboratories. The first such and best known is the LUNA project [2] at the Laboratori Nazionali di Gran Sasso of INFN, in Gran Sasso, Italy. Several other projects are under development or in planning phase in USA and China. To install an underground facility is not an easy task and, therefore, dedicated projects for nuclear astrophysics could so far be planned around existing or planned larger underground physics laboratories. We present here the case where we combine the use of a new small accelerator situated at the surface on the premises of the IFIN-HH institute with an ultra-low background laboratory the institute has in a salt mine in Slanic-Prahova, about 120 km North of Bucharest. The 3 MV tandem accelerator [3] can deliver low energies and relatively large beam current (tens of μA) of most stable elements from protons up. In the microBequerel ultra-low background [4] laboratory we can measure then samples with activities down to mBq. That is due to its special natural conditions that lead to very low gamma-ray background from natural radioactivity. If the reactions under study produce activations with life times that allow the transfer to Slanic, we can gain significantly in detection sensitivity.

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[*] Corresponding author.
E-mail address: livius.trache@nipne.ro (L. Trache).

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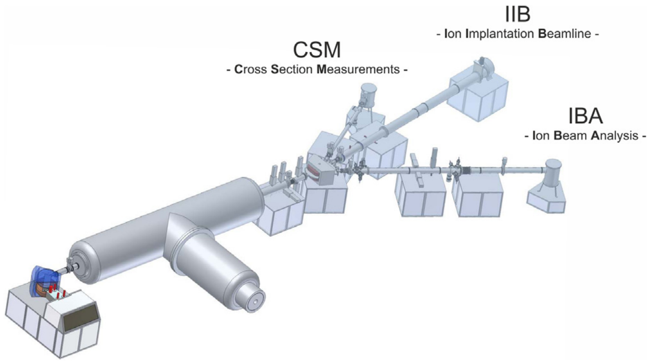


Fig. 1. Outline of the 3 MV tandem accelerator facility.

Table 1
Beam currents measured after the 90^0 deflecting magnet in the accelerator Faraday cup [3]. A full list is available on http://www.nipne.ro/research/departments/dfn.php.

Ion source	Ion species	Typical current [μA]
Duoplasmatron	$^{1}H^{-}$	>40
	$^{4}He^{-}$	>3
Cs sputter	$^{11}B^{-}$	>40
	$^{12}C^{-}$	>80
	$^{16}O^{-}$	>80
	$^{28}Si^{-}$	>80
	$^{31}P^{-}$	>40
	$^{58}Ni^{-}$	>70
	$^{63}Cu^{-}$	>70
	$^{75}As^{-}$	>10
	$^{197}Au^{-}$	>80

The paper is divided as follows: Section 2 describes summarily the accelerator, its beam currents, stability and energy calibration. Section 3 describes the characteristics of the microBequerel laboratory that are important in these particular nuclear astrophysics experiments. The ultra-low gamma-ray background is demonstrated and the HPGe detector efficiency calibration is emphasized. In Section 4 we present the main features of the combination accelerator — salt mine laboratory using the $^{13}C+^{12}C$ reaction at low energies, down into the equivalent of the Gamow window of the $^{12}C+^{12}C$ reaction of crucial importance for nuclear astrophysics. Results of two other reactions induced by alpha particles are mentioned. Section 5 presents the conclusions of the study. Short descriptions of the facilities were included before in preliminary reports of the reactions studied [5–7] and the results of the $^{13}C+^{12}C$ fusion reaction studies are submitted for publication elsewhere [8].

2. The 3 MV TANDETRON™ accelerator

The 3 MV Tandetron™ was designed and built by High Voltage Engineering Europa B.V. and commissioned at IFIN-HH in 2012. Its original intended use was Ion Beam Analysis (IBA) with various methods: Rutherford Backscattering (RBS), Elastic Recoil Detection Analysis (ERDA), Particle Induced X-rays Emission (PIXE), Particle Induced Gamma-rays Emission (PIGE), Nuclear Reaction Analyses (NRA) and ion implantation, as described in Ref. [3]. The layout of the Tandetron™ and its beam lines are shown in Fig. 1. Fig. 2 is a picture of the overall arrangement in the accelerator hall. With the final goal of establishing a solid line of research in nuclear astrophysics at the Bucharest accelerators and laboratories of IFIN-HH, we have performed experiments to check the limits of the one method that seemed appropriate and for which the institute has or could acquire installations: the activation method. We used for irradiation the new 3 MV Tandetron™ accelerator.

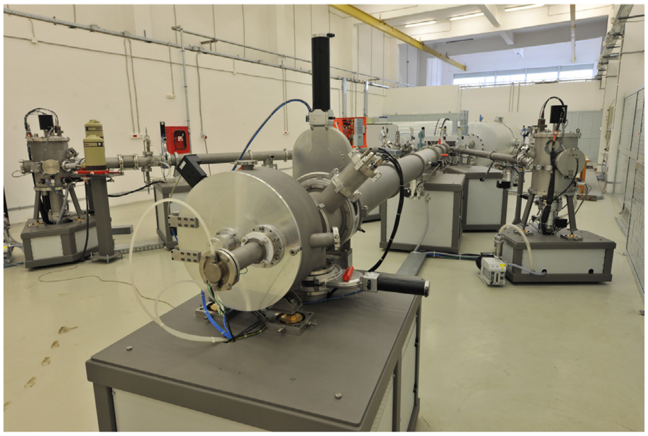
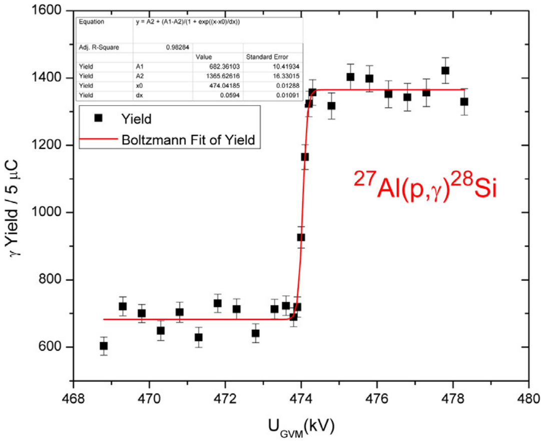


Fig. 2. The 3 MV Tandetron accelerator at IFIN-HH. NA measurements were done on the beam lines in center and at right.



Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))		
Adj. R-Square	0.98284		
		Value	Standard Error
Yield	A1	682.36103	10.41934
Yield	A2	1365.62616	16.33015
Yield	x0	474.04185	0.01288
Yield	dx	0.0594	0.01091

Fig. 3. Excitation function for the $^{27}Al(p, \gamma)^{28}Si$ at 992 keV resonance.

We noticed that while there are many small proton accelerators used specifically for NA, some underground, not many accelerators for alpha and light ions are dedicated to nuclear astrophysics direct measurements. This could be a niche. Early on we realized that the accelerator has potential for use in nuclear astrophysics and tested its characteristics. We tested that it:

- can reliably and stably perform for terminal voltages of 0.2 – 3.3 MV;
- provides stable currents for long periods of time, typically needed for measurements that need to last days or weeks;
- provides relatively high currents for a variety of beams.

The beam currents obtained for a few ion species are shown in Table 1. In particular, the beam intensities in the order of 1 pμA for alphas and at least ten times more for ^{12}C gave us the idea that one can use the accelerator to study light ion–ion reactions of relevance for nuclear astrophysics.

The accelerator high voltage is monitored by a generating voltmeter (GVM) that provides feedback for the Tandetron™ driver. GVM requires periodic calibration and for this work the resonant reaction $^{27}Al(p, \gamma)^{28}Si$ was used [9,10]. The well-known narrow resonance at $E_p = 992$ keV was scanned in 0.1 kV steps and the excitation function is given in Fig. 3, which is included only to illustrate the actual performances of the procedure. In order to determine the calibration curve two more cross-section maxima were measured near 1317 keV, respectively 1381 keV [11].

3. The ultra-low background microBequerel laboratory

Salt mining has in Romania a history that goes back to ancient times, but in Slanic-Prahova the first mine was only opened in 1688.

Fig. 4. The location of the mBq laboratory inside the Slanic salt mine.

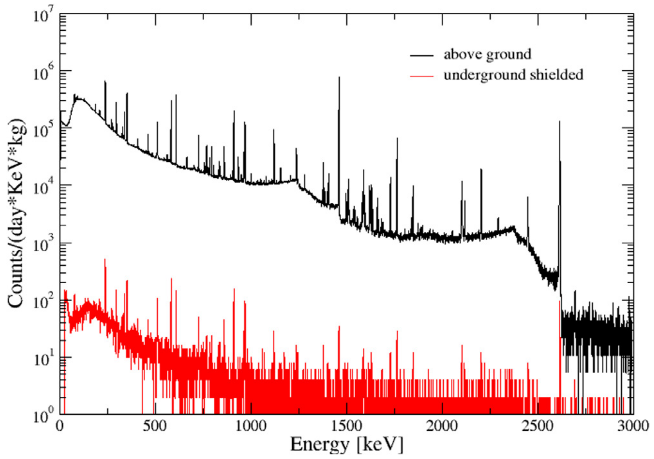


Fig. 5. Natural background from the μBq laboratory collected with the same HPGe: top is above ground, bottom is underground shielded.

Slanic Prahova is situated about 100 km north of Bucharest. The Unirea salt mine has been open since 1943 with salt exploitation performed until 1970 [12]. After the latter, sections of the mine were opened for visitors. In 2006 the microBequerel (μBq) laboratory of IFIN-HH has been constructed and fully commissioned. The depth of the mine is around 210 m (~600 m water equivalent) [13]. The consideration for which this location has been chosen is the very low natural radioactivity, due to the fact that walls do not present cracks and due to the high purity of the salt [14] (see Fig. 4).

The Underground Laboratory in the Unirea salt mine, Slanic Prahova (μBq), is located at about 2 h drive North of Bucharest. Environmental conditions in the salt mine are very stable year-round: temperature between 12 and 13 °C, humidity 60%–65% approximately, area of 70 000 m^2, height between 54 and 58 m, the distance between the walls is between 32 and 36 m, volume is 2.9×10^6 m^3. In this mine a laboratory was built and it performs measurements using gamma ray spectrometry in ultra-low radiation background. The average dose underground was found 1.17 ± 0.14 nGy/h, approximately 80–90 times lower than the dose at the surface [4,14]. Ambient background radiation comes from:

(i) natural radioactivity (especially from the decay of ^{238}U, ^{232}Th and ^{40}K);
(ii) neutrons from (α, n) reactions and fission;
(iii) cosmic rays (μ, ^{1}H, ^{3}H; ^{7}Be, ^{14}C ...).

The first two sources are particularly low in this mine due to its thick and compact salt walls. Fig. 5 compares γ-ray spectra measured above ground and underground. The top spectrum shows that the strongest components of the γ rays spectrum at E_γ < 2.6 MeV is associated with the natural environmental radioactivity and exhibits intense characteristic lines. At higher energies, the background originates mostly from cosmic rays (iii). The natural radioactivity is significantly reduced for measurements in the underground laboratory (bottom spectrum). From Fig. 5 it can be seen that the measured background radiation (using a protection shield, produced by Canberra Ind., consisting of 15 cm Pb and 5 cm Cu) is about 4000 times smaller compared to the background spectrum measured at the surface. This is the major advantage we wanted to test and use in the current measurements. The total counts from 40 to 2700 keV are compared above. The integrated underground rate for this gamma-ray energy region was 25,870 counts in 48 h, that is 539(4) cts/h, (statistical uncertainty only). For comparison we can refer the reader to two underground installations: LUNA at Laboratori Nazionali Gran Sasso [15] and CASPAR at Sanford Underground Research Laboratory in Lead, SD, USA [16]. Both consist of accelerators and detection setups, and are very deep under (3800 mwe and 4300 mwe, respectively). Therefore, we can compare only the gamma-ray backgrounds at these places with the one in Slanic, when similar data exist. The underground LUNA facility (accelerator and detectors), under 1.4 km of rock in Gran Sasso, reports [15] a rate of 4870 cts/h in the 1461 keV peak (^{40}K) and 1325 cts/h at the 2614 keV peak (^{232}Th series) with a 137% relative efficiency HPGe detector. In a similar detector in Slanic we measure a rate of 1.81 cts/h and 4.8 cts/h in the same peaks. With special shielding, including anti-radon box with dry nitrogen gas flow around the detector, the rates at LUNA become 0.93 cts/h and 0.42 cts/h (setup B in Ref. [15]) for the same two representative gamma-ray background peaks and with extra shielding these rates were reduced by another factor of 2. More recently, at the location of LUNA2 [17] the rates for the same two gamma lines are reported as 2190(10) cts/h and 680(15) cts/h unshielded, and 14.8(3) cts/h and 15.2(3), respectively, for the shielded HPGe detector of 100% relative efficiency (no anti-radon box). At CASPAR, the gamma-ray background in the region 40–2700 keV is essentially the same underground as is at the surface (due to the proximity of rock walls). With shielding the background decreases by a factor 100 in the energy region mentioned [16]. These two latter underground locations are vastly superior in terms of shielding against muons and neutrons, which reflects in reduced background in gamma-ray spectra at E_γ > 2.7 MeV.

4. Test case: the ^{13}C+^{12}C reaction studies

The first reaction that we studied was ^{13}C+^{12}C, together with the group from IMP (Institute of Modern Physics) Lanzhou, China. This reaction leads to an activation appropriate for our tests: ^{24}Na, which has a half-life of 15 h and is formed by one proton evaporation from the compound nucleus ^{25}Mg. Our choice of test case was motivated by the need to test the characteristics of the facility as well as to study the fusion reaction mechanism deep under the Coulomb barrier in a system close to the ^{12}C+^{12}C reaction of great importance in nuclear astrophysics. We studied the ^{13}C+ ^{12}C fusion reaction in the energy range of E_{lab} = 4.6 up to 11 MeV using the activation method and gamma-ray spectroscopy. That translates into an energy range E_{cm} = 2.2 – 5.6 MeV, which is deep into the Gamow window for the ^{12}C+^{12}C burning at relevant stellar temperatures [18]. Beams of ^{13}C were obtained from the sputtering source with intensities of 0.4 up to 15 pμA and different charge states. The targets used were made of pure natural graphite with a thickness of 1 mm. For the energies where the irradiation time was longer it was necessary to cool-down the targets using a dielectric coolant system. After a number of tests, we found a situation where the current was reliably measured with the target that was also a Faraday cup (see Fig. 6). A total of 71 targets were irradiated and measured. For prompt gamma-ray measurements, a HPGe detector of 100% relative efficiency was placed at 55^0 with respect to the beam axis in forward direction. We succeeded to determine the contributions from p, n and α evaporation channels for the energies where reaction cross sections were high enough to be measured in the accelerator hall (above 6.4 MeV). This is not a point important here, it is detailed further in Ref. [19]. The final irradiation setup is shown in Fig. 7.

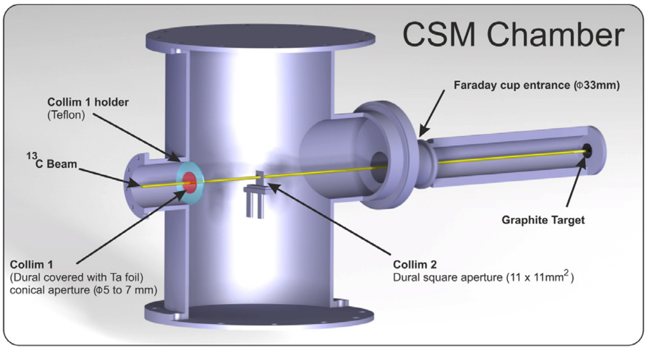


Fig. 6. Irradiation chamber schematics.

Fig. 7. The irradiation chamber. A HPGe detector placed inside the lead castle to measure prompt gamma rays.

The induced activities have been measured by detecting the γ rays following the β decay of ^{24}Na reaction product with well shielded HPGe detectors at GammaSpec [20], NAG (Nuclear Astrophysics Group - our group's laboratory) and μBq laboratories. Because of its sufficiently long half time, ^{24}Na was excellent for the procedure we used: up to one day of irradiation (depending on the incident energy), transfer to Slanic in 2.5 h and about one day of de-activation measurements, during the irradiation of the next target, and so on. At bombarding energies higher than 5.6 MeV, activities were also measured in the certified setup GammaSpec situated next door, in a basement of the same department. In these 3 laboratories, the cascading gamma rays (1369 and 2754 keV) [21] were detected with HPGe detectors of 30% (at GammaSpec), 100% (at NAG) and 120% (at μBq in the salt mine) relative efficiency. For efficiency calibration we used sources with well-known activities, like: ^{152}Eu, ^{133}Ba, ^{60}Co, ^{137}Cs, ^{241}Am.

The coincidence summing correction was determined by measuring one target placed in close (1 mm) and far geometry (15 cm). Calibrations and measurements performed in similar conditions allowed us to reduce the systematic uncertainties associated with the experimental data corresponding with the range $E_{c.m} = 2.2$–5.6 MeV below 10%. Targets irradiated at the same energy and in similar conditions were measured at GammaSpec and in the salt mine. The differences between the results were within the estimated errors. As such we could verify the efficiency calibration of the 120% relative efficiency HPGe detector used in the underground laboratory Slănic and gives us confidence in the absolute values of the cross sections measured. Fig. 8 shows 3 spectra collected in the salt mine: (a) the gamma ray spectrum of a target that was irradiated at the energy of 8.6 MeV, (b) and (c) show the spectra of targets irradiated at $E_{beam} = 4.8$ MeV without and with background subtraction. The background peaks left in (c) are due to variations in background during the 3.9 days of measurement of three different samples. These variations are very small and only visible relative to the very low activities of the samples we measured. They occur simply due to the presence/absence of the experimenters or of new devices in the measuring hall. The apparent peak at E = 2614 keV is in fact due to statistical fluctuations in spectra subtraction of the very large numbers making the out-of-scale tall peak in (b).

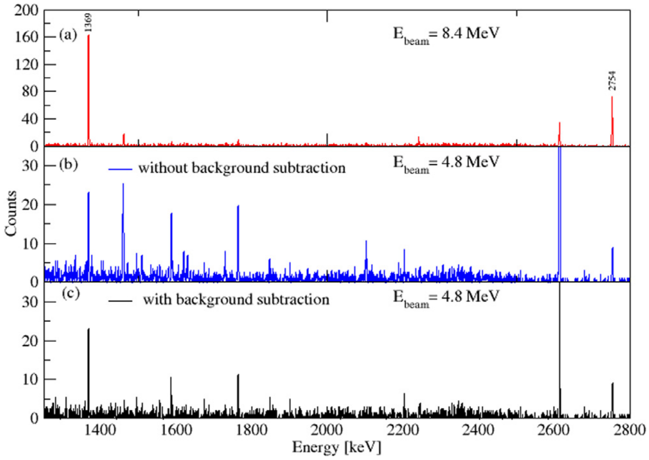


Fig. 8. Spectra measured at μBq for two targets irradiated at 8.4 (a) and 4.8 MeV (b, c). Only the two peaks of interest are labeled. The others are from background.

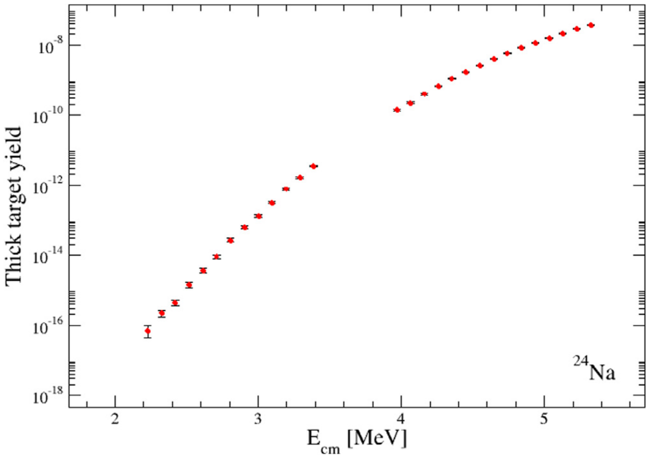


Fig. 9. Thick target yield for the proton evaporation channel.

To determine the thick target yield we used only the 1369 keV peak which has a branching ratio of $I_\gamma = 99.9935\%$ [21]. Firstly, the activity of the targets at the end of irradiation procedure and the beam current integrated in time (corrected step-wise for decay during irradiation) was determined:

$$\Lambda = \frac{\lambda C}{\varepsilon_\gamma I_\gamma t_c (1 - e^{-\lambda t_c})} e^{\lambda \Delta t} \tag{1}$$

where, C are the net counts of full energy peak of a gamma transition, ε_γ is the efficiency, I_γ the absolute branching ratio for 1369 keV γ-ray, t_c is the counting time and Δt is the time between the end of irradiation and the start of counting. Secondly, the thick target yield was determined as the ratio between the activity and beam current integrated in time (Fig. 9). The final step was to determine the proton cross section using the thick target method. Projectiles with different energies, in our case E and E-ΔE, where $\Delta E = 0.2$ MeV will penetrate two different depths, and the cross sections in Fig. 10 are determined by differentiating the yields and using stopping ranges calculated with SRIM [22].

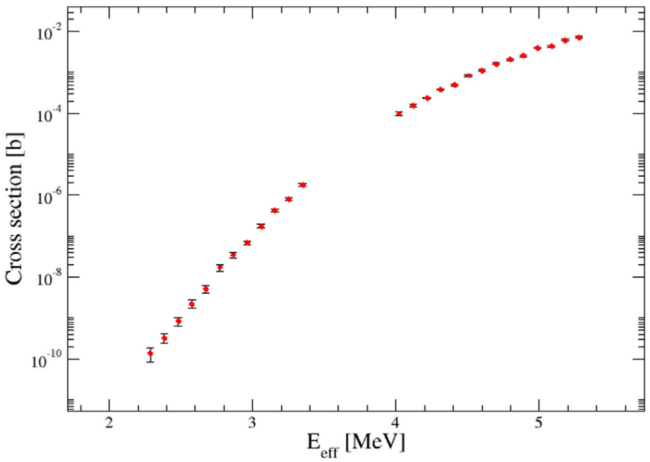


Fig. 10. The proton evaporation, ^{12}C(^{13}C,p)^{24}Na, cross section from activation measurements for: E = 2.2–3.4 MeV and from E = 4.0 up to 5.2 MeV; preliminary results.

The activities of irradiated targets measured both in the underground and surface laboratories allowed to determine the limit of detection for cross sections to be of the order of ∼100 pb. Essentially, we achieved an increased sensitivity of these measurements by about a factor 100 over the best experiments performed so far [23], which could only measure down to E_{cm} = 2.64 MeV. Note that the latter used $\beta - \gamma$ coincidences to clean up the activation spectra. [Note: we determined there are no other reactions making ^{24}Na. The targets are >99.9% pure carbon (by Kurt J. Lesker Co., Jefferson Hills, PA). The reaction ^{13}C on the 1% ^{13}C isotopic impurity in the targets does not lead to ^{24}Na due to the prohibitive Q-values (1.5 and −0.7 MeV for d, or pn evaporation, compared with 11.8, 11.4 and 8.3 MeV for α, n and p evaporation).]

The facility was also used for the study of two other reactions induced by α particles. The first one was α+^{64}Zn. During the experiment we irradiated natural thick zinc targets (1 mm) by alpha beams with energies in the laboratory frame between 5.4–8.0 MeV, in steps of 0.2 and 0.25 MeV. Total beam time was 140 h and the beam current varied from 0.2 to 0.7 μA. For this energy range we measured the proton evaporation channel, ^{64}Zn(α,p)^{67}Ga with a $T_{1/2}$ = 78.28 h, which is one of the three channels that lead to activation [24]. In the underground laboratory gamma rays of E_γ = 184.6, 209.0, 300.2 and 393.5 keV were detected [21]. In this case the sensitivity is increased again by a factor of around 100 compared with previous results [25]. For the second reaction, α beams impinged on natural Ni targets. In this case the reaction cross section for the (α, γ) channel was determined with a similar sensitivity. The details of these experiments and the results will be the subject of other publications.

5. Conclusions

We present a new facility for nuclear astrophysics. We show that direct measurements can be successfully and reliably made using a small tandem accelerator for irradiations and an ultra-low background laboratory located underground in the Slănic-Prahova salt mine for de-activation measurements. Both facilities belong and are operated by IFIN-HH. We conclude and show that the accelerator is competitive to study reactions induced by alpha particles and light ions. After irradiation, the samples are transferred to the salt mine, about 120 km away from IFIN-HH Măgurele-Bucharest. The activity of the resulting samples is measured by high resolution, high efficiency HPGe detector(s) in an ultra-low gamma-ray background environment. This reduced natural radioactivity background is due to the natural conditions in the salt mine: the salt is pure with no radioactive contaminants, rocks are far away, and the salt walls are compact, with no cracks for radon gas to migrate. The salt mine is only about 210 m under surface (∼600 mwe), therefore cosmic radiation is not much inhibited, but its produced background is not important in our type of measurements. This procedure is limited for cases where the resulting activity has lifetimes larger than 1–2 h, that is, comparable to the transfer time of the samples. If a gain of a factor around 100 in sensitivity is achieved - the actual number may differ depending on the de-activation gamma-rays, their energies and branchings - a loss of activity of 2 to 4 times during samples' transfer, may still allow an important gain in cases of real importance for NA. For shorter halftimes different methods will be applied to avoid the time consuming transfer of samples (primarily beta-gamma coincidences).

Summarizing, the pros of this facility are:

– a small but stable accelerator with relatively high currents, including for light ions;

– a laboratory with ultra-low gamma-ray background in a salt mine for de-activation measurements with high resolution and efficiency HPGe detectors;

– the ability to determine absolute values for the cross sections measured — the GammaSpec utility is certified, cross calibrated internationally.

The limitation stems from the distance between the accelerator and the salt mine, which makes it inefficient for activities with half-lives shorter than 1–2 h.

For the ^{13}C+^{12}C case that was the most appropriate test of the procedure, activities as low as 3 mBq could be measured, and cross sections of about 100 pb. Two α induced cases were also studied, using the salt mine laboratory, with satisfying results. For example for the ^{64}Zn(α,p)^{67}Ga case we were able to determine a cross section of the order of 30 nb.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

D. Tudor: Data curation, Writing — original draft. **L. Trache:** Conceptualization, Writing — review & editing, Supervision. **A.I. Chilug:** Data curation. **I.C. Stefanescu:** Investigation. **A. Spiridon:** Data curation. **M. Straticiuc:** Methodology. **I. Burducea:** Investigation. **A. Pantelica:** Methodology. **R. Margineanu:** Project administration. **D.G. Ghita:** Investigation. **D.G. Pacesila:** Investigation. **R.F. Andrei:** Investigation. **C. Gomoiu:** Data curation. **N.T. Zhang:** Data curation, validation. **X.D. Tang:** Conceptualization, Supervision.

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Nuclear astrophysics studies at NIPNE

Livius Trache

Horia Hulubei Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania

Abstract. I will present results of doing nuclear astrophysics research at the National Institute for Physics and Nuclear Engineering, Bucharest-Magurele in the last 2-3 years.
Own Nuclear Astrophysics Group (NAG) is focused on the basic types of experiments:

- Direct measurements at low and very low energies with ion or alpha beams from the local 3 MV tandetron accelerator. We concentrate on activation measurements. The use of the ultra-low background laboratory in a salt mine at Slanic-Prahova, about 120 km away and of a beta-gamma coincidence unit at home is providing competitive sensitivity.
- Indirect measurements done with beams at international facilities with radioactive beams: TAMU and RIBF RIKEN.

With help from colleagues, I will mention some theory advances, too.

1 Introduction

I will start with thanking, twice, the organizers: for inviting me and for suggesting the title and subject of this talk. The charge was to present the activities in nuclear physics for astrophysics at my home institution, the National Institute for Physics and Nuclear Engineering (NIPNE) in Bucharest-Magurele, also known as IFIN-HH from its Romanian name. This charge is similar with the one given me two editions ago, and I was glad to oblige. For some reasons, in particular the loss of manpower, the experimental activities were concentrated in one group, the Nuclear Astrophysics Group (NAG), which at some point had 7 members. I will, therefore, concentrate in presenting its work, and only at the end list in a few sentences the progress in theory by other groups or scientists of NIPNE. While the main lines of work are the same as presented earlier [1], we are now at the point where we went from plans and proposals to results. One further development is that some of the young members diversify by working in groups at foreign institutes or universities. I will, however, talk only about their work derived from specific plans in NIPNE.

We continued the two main types of nuclear astrophysics experiments:

- direct measurements, done at home, using the 3 MV tandetron, mainly using activation techniques. These use low-energy stable beams, an ultra-low background laboratory and a new beta-gamma coincidence setup. The $^{12}C+^{12}C$ fusion reaction was the focus of one long set of measurements, (α,γ) reactions in the rp-region of nuclei was another.
- indirect methods, using rare ion beams or exotic nuclei produced at international facilities.

I will treat each of these in the following sections.

In the end I will briefly state the interest in developing theory support tools for our indirect methods and the coupling of nuclear structure theory to nuclear processes that take place in stars.

2. Experiments with low-energy stable beams

In the last years we studied the possibility to do direct measurements for nuclear astrophysics in IFIN-HH. (as for example (p,γ), (α,γ) or ion-ion fusion), We realized that we can be competitive using alpha and light ion beams, but not using proton beams. The small 3 MV tandetron accelerator can deliver stable and relatively intense beams of light ions and alphas. A list is in [1] and the complete list of beams available can be found at http://www.nipne.ro/research/departments/dfn.php under "Accelerators/ 3 MV tandetron". These two types of beams were used in our experiments.

2.1 The study of ion-ion fusion

The one experiment we worked most and with results was the study of the $^{13}C+^{12}C$ reaction. While this is not a reaction of importance in nuclear astrophysics, we and our collaborators from the Institute of Modern Physics, Lanzhou, China, claim that its study can help to understand the fusion mechanism for the $^{12}C+^{12}C$ reaction at very low sub-barrier energies. The latter reaction is very important in stars, and reliable experimental information is not available in the Gamow window, despite many attempts using direct [2] and references therein, or indirect methods [3]. We claim that our measurements with ^{13}C beams at energies deep in the Gamow window help to understand the fusion mechanism and gives an upper limit for the fusion cross section of the $^{12}C+^{12}C$ reaction. The measurements of the latter are complicated not only by the very small cross sections, but also by the resonances that were found to dominate the region adjacent to that important in astrophysics (see [3] and references therein). The use of the ^{13}C induced fusion is based on the observation that its fusion excitation function is smooth when compared with that of $^{12}C+^{12}C$ and has the same trend as it goes down in energy (it touches the top of the resonances). Experimentally, the measurements at very low energies are helped by that that one fusion-evaporation channel $^{13}C+^{12}C\rightarrow^{25}Mg^*\rightarrow^{24}Na^*+p$ leads to a radioactivity which has $T_{1/2}$=15.0 h. This enables the use of activation techniques, many times more sensitive at low energies, and the halflife is excellent for using the ultra-low background laboratory IFIN-HH has in the salt mine in Slanic-Prahova, about 120 km away. The procedure we used and the main characteristics of the facility accelerator + salt mine laboratory are described in a forthcoming publication [4].

Summarizing, the pros of this accelerator + salt mine facility are:

- a small but stable accelerator with relatively high currents, including for light ions;
- a laboratory with ultra-low gamma-ray background in a salt mine for de-activation measurements with high resolution and efficient HPGe detectors;
- the ability to determine absolute values for the cross sections measured - we have an utility (GammaSpec), which is certified and cross calibrated internationally.

The limitation stems from the distance between the accelerator and the salt mine, which makes it inefficient for activities with half-lives shorter than 1-2 hours.

Prompt gamma-rays were measured with HPGe detectors, and gammas from de-activation were measured in three setups, carefully calibrated and intercompared. With our measurements at energies E_{cm} = 5.5 – 2.3 MeV we got in the region of energies corresponding to the Gamow window and could measure a cross section of 130(30) pb at the lowest energy point. This is 100 times lower than the best experiment so far at a surface laboratory. At higher energies we could measure prompt gamma-rays, but at the lowest energies we had to do one day of irradiation, transfer to Slanic in 2.5 hrs and about one day de-activation measurement there, during the irradiation of the next target, and so on. For the lowest two energy points, at E_{lab}=4.6 and 4.8 MeV, we irradiated 3 targets each.

The result of the $^{13}C+^{12}C$ project is that we disagree with the so-called hindrance model [2] for the fusion of $^{12}C+^{12}C$ and extend the astrophysical S-factor down to lower energies in trend with many potential model predictions and in good agreement with the predictions of Caughlan and Fowler [5]. The results were submitted for publication [6].

In continuation of this project we started working on other combinations ion-ion to measure deep sub-barrier fusion. Because activation is the method with best sensitivity, but many residual nuclei in this region do not have lifetimes sufficiently long for efficient transfer to the salt mine in Slanic, we designed and made a setup for efficient beta-gamma coincidences that we call BEGA. It was tested with sources, it works, and now we are testing to determine the lower limits of the lifetimes we can access with it located in the accelerator target room.

2.2 Alpha-beam induced reactions at low energies

Two reactions were studied with alpha beams of low energy: ^{64} Zn+α and ^{58}Ni+α. During experiments natural thick Zn and Ni targets (1 mm) were irradiated by alpha beams with energies in the laboratory frame between 5.4-8.0 MeV, in steps of 0.2 and 0.25 MeV. In the first case the total beam time was 140 h and the beam current varied from 0.2 to 0.7 mA. For the energy range above we have measured the proton evaporation channel, ^{64}Zn(α,p)^{67}Ga with a $T_{1/2}$=78.28 h, which is one of the three channels that lead to activation**.** De-activation gamma rays of E_γ=184.6, 209.0, 300.2 and 393.5 keV were detected. In this case the sensitivity is increased again by a factor of around 100 compared with previous results [7]. For the second case, the reaction cross sections for the ^{58}Ni (α, γ) ^{62}Zn and ^{58}Ni (α, p) ^{61}Cu channels, with half-lives $T_{1/2}$(^{62}Zn)=9.26 h and $T_{1/2}$(^{61}Cu)= 3.33 h, respectively were determined with a similar sensitivity. In the cases of both Zn and Ni targets the transfer to the salt mine laboratory could be used at the lowest energies. The details of these experiments and the results will be the subject of other publications. One example of comparisons of our data with previous experiments is shown in Figure 1 below (A. Chilug et al., to be published). The activation method (labelled "IFIN decay") is significantly more sensitive than the prompt, in-beam measurements and covers 6-7 orders of magnitude.

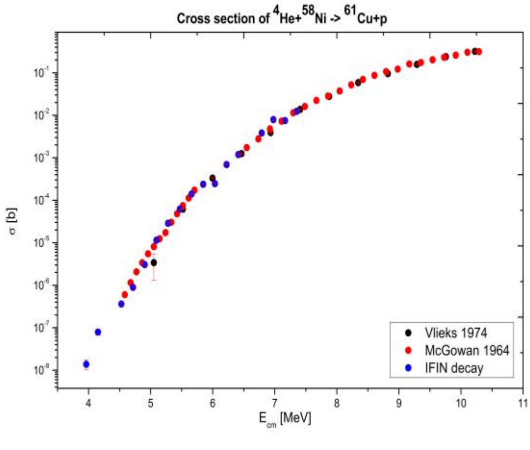

Figure 1. Comparison between the results obtained in IFIN and in the other experiments.

3. Indirect measurements

The indirect methods in nuclear astrophysics (IMNA) are those methods in which we make studies using nuclear reactions at much higher energies than those available/important in the stars, at typical nuclear laboratory energies that are 100-1000 times larger. We seek and obtain in these measurements information which is later used to evaluate reaction rates at very low energies, relevant for nuclear astrophysics. Experimentally, there are advantages related firstly to the larger cross sections of the reactions employed and secondly to the fact that by using Radioactive Ion Beams (RIB), available lately in several laboratories, one can extend our measurements to stellar reactions which involve unstable partner(s). These reactions are overwhelmingly the most numerous in stellar processes. So far direct astrophysical measurements with RIB are not possible (but attempts and progress are made in this direction). In IFIN-HH we do not have RIBs, therefore this type of measurements we can only pursue at outside facilities. (In parenthesis: these involve proposals and PAC approval and may take a lot of time. A bonus is that they imply collaborations, sometimes large collaborations!) Important to notice in IMNA is that good, reliable theoretical support is crucial; I will briefly argue on this at the end of the paper.

NAG was involved in many experiments and in some theory subjects in the last years. I will mention only those where we had a leading role, or at least an important one.

3.1 Breakup of loosely bound radioactive nuclei

I was talking about this breakup subject several times. The basic idea is that for loosely bound projectiles in both proton Coulomb and nuclear breakup X→Y+p reactions information can be obtained that is directly relevant to radiative proton capture reactions Y(p,γ)X in stars. We were proposing and/or preparing experiments on this subject, this time we carried a long awaited ^{9}C Coulomb and nuclear breakup experiment at RIBF of RIKEN in Wako, Japan. The experiment was carried out at the SAMURAI spectrometer using a secondary ^{9}C beam at 160 MeV/nucleon. It was the first in a series of four proposed (and PAC accepted) experiments with proton-rich radioactive beams at RIBF, the HI-p collaboration. This was a first at a facility that has so far excelled in producing neutron-rich secondary beams. Moreover, it was notable that a neutron-rich primary beam, ^{18}O at 230 MeV/nucleon was used to produce a very proton-rich ^{9}C secondary beam. Our group has worked with the RIBF group to obtain a reasonably intense and clean beam: ^{9}C 87%, plus ^{8}B and ^{7}Be impurities. Inclusive and exclusive measurements at energies around 160 AMeV for ^{9}C were carried out in order to evaluate the astrophysical S_{18} factor for the inverse process ^{8}B(p,γ)^{9}C at energies in the region of astrophysical interest. This radiative proton capture on ^{8}B is important in the hot *pp* chains, in explosive Hydrogen burning (*ppIV* and *rapI*), at temperatures between $0.05 < T_9 < 1K$, as possible alternative paths across the A=8 mass gap. Another goal of this experiment was a detailed study of the breakup reaction mechanism. A C target was used for the nuclear breakup and a Pb target for the Coulomb dissociation study. The data analysis is not finished at this time, a preliminary report was presented in Dec. 2018 at the Nucleus-Nucleus Collisions 2018 conference, Saitama, Japan and a publication was accepted [8]. It reports in particular about the design and functioning of a Si detector system and its attached electronics used in front of SAMURAI spectrometer, right after the target.

3.1 Spectroscopy of resonances

In many reactions in addition to a continuous component of the astrophysical S-factor, low energy resonances play a role, sometimes a decisive role. To determine their position (E_{res}) and their resonance strength any spectroscopic method is valid. We worked on two types of experiments.

One involves beta-delayed proton decay (βp) of exotic nuclei. Started by the author at Texas A&M University a few years back, we advanced in instrumentation in the last few years and we had the first experiments. It works like this: the low energy resonances that contribute to the stellar reaction rates for proton radiative captures can, in cases where energy and selection rules permit, be populated through beta-decay. Then, these states do proton decay. However, the proton energies will be very small for the most important resonances and these energies cannot be easily measured. We designed a method and detectors to reach down at energies as low as E_p=100 keV without being affected by the always present and overwhelming β background. It is based on a gas detector working in ionizing chamber regime and a special amplifying device called micromegas, a region of space between two electrodes separated by 256 microns that works in an avalanche regime that delivers good amplification of the original signal by up to 10^4, while keeping a very good resolution. Two versions of the detector called ASTROBOX [9] and ASTROBOX2 [10] were built. A local version ASTROBOX2E was put together in our group. I send you to these publications for details. The βp-decay of ^{23}Al, ^{31}Cl and ^{35}K were measured and we plan soon to measure ^{27}P, all at Texas A&M University with exotic beams produced and separated by the superconducting cyclotron K500 and the mass separator MARS.

Another type of experiments was one of gamma-ray spectrometry. We have measured the reaction ^{28}Si(α,nγ)^{31}S at the 9 MV tandem of IFIN-HH using the ROSPHERE detector array with neutron detectors added. This analysis is also not finished yet and I will not further describe it here.

4. Theory for nuclear astrophysics

I will only state here (as I did in the presentation at ENNAS 2019) that there are groups/persons at IFIN-HH working on three different topics of importance in nuclear astrophysics. These are:

- support for IMNA: we have a long-term program to understand and describe reactions between nuclei, including those with RIB. For this purpose, we work with prof. F. Carstoiu on the problem of optical model potentials [11];
- the evaluation of the contribution of excited states in reactions and processes that take place in hot stellar plasma – prof. Alexandrina Petrovici and her group [12];
- baryonic equation of state under extreme conditions – prof. Adriana Raduta [13].

5. Conclusions

I could sketch here the few directions of work and progress in nuclear astrophysics at IFIN-HH Bucharest-Magurele. I insisted on experiments and only mentioned briefly theory.

I should mention too that essentially the same NAG group initiated and organized a few events in the field, events that you may have taken part in. One was the training school (a hands-on experiment) for the COST action CA16117 ChETEC, one other the Carpathian Summer School of Physics, the sister of ENNAS, attended again by around 100 people in its latest editions (2016 and 2018 [14]), and the third was the ECT* workshop in Trento, Italy, Nov. 5-9 2018 with a title relevant “Indirect Methods in Nuclear Astrophysics” [15].

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