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Nuclear Astrophysics at IFIN-HH

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Abstract. I will present the possibilities and some results of doing nuclear astrophysics research in IFIN-HH Bucharest-Magurele. There are basically two lines of experimental activities: (1) direct measurements with beams from the local accelerators, in particular with the new 3 MV Tandatron accelerator. This facility turns out to be competitive for reactions induced by α -particles and light ions. Extra capabilities are given by the ultra-low background laboratory we have in a salt mine about 2.5 hrs. driving north of Bucharest; (2) indirect measurements done with beams at international facilities, in particular at those providing Rare Ion Beams. Completely new and unique opportunities will be provided by ELI-NP, under construction in our institute.

1. Introduction

I am glad to be again at this school! It is one of the three pillars of the European Network of Nuclear Astrophysics (ENNAS) and together with the Russbach, Austria, winter school and the Carpathian summer school in Sinaia, Romania, does an excellent service to the community. I did not want to miss coming and lecturing here. This time I did not chose the title, the organizers chose it for me. And I was glad to oblige! I will, therefore, talk about research in nuclear astrophysics (NA) at my home institute IFIN-HH, a home that I re-joined 3 years ago after a two decades absence. Besides my own group that I try to organize, there are groups with at least part of their activity motivated by NA at the accelerators the institute has. That is when we refer to experimental work. There are theoretical activities motivated by NA and I will briefly mention those, but not insist.

You (students) have learned already at this school, and I am sure you did know already, that, *grosso modo*, in experimental nuclear astrophysics we use:

- 1) direct measurements, that is, we measure the reactions that happen in stars at exactly the energies they happen, or as close to them as possible and
- 2) indirect measurements.

The first type of measurements are difficult mostly due to the very low cross sections which are typical for the very low energies available in stars. Only cases where the reactions are possible with the available projectile-target combinations (stable nuclei) can be studied so far. Particular care must be taken to get accelerators with high currents, good targets, high detection efficiencies and conditions to maintain good signal/background ratios. I will show in the next section that we can do competitively a few types of these measurements in Bucharest. The indirect methods are those methods in which we make studies using nuclear reactions at much higher energies than those available/important in the stars, typical nuclear laboratory energies 100-1000 times larger, seeking information which is later used to evaluate reaction rates at very low energies. Here there are advantages related firstly to the larger cross sections of the reactions employed and secondly to the



fact that by using Radioactive Nuclear Beams (RNB), available lately in several laboratories, we can extend our measurements to stellar reactions which involve unstable partner(s). In IFIN-HH we do not have RNB so far, therefore this type of measurements we can only pursue at outside facilities. Important to notice is that good, reliable theoretical support is crucial in all indirect methods; I will briefly argue on that later.

2. Direct measurements

The goal of these type of measurements is to measure cross sections in the Gamow window. This means very low energies and consequently very low cross sections, a fact easily understandable for the case of reactions between charged particles (as for example (p,γ) , (α,γ) or ion-ion fusion), as due to the Coulomb barrier. As such, it is no wonder that the first measurements in the Gamow window are only about one decade old! That could be done in an underground lab like that in the National Laboratory Gran Sasso and several other labs are now working with very light projectiles like p , d , or ${}^3\text{He}$ and different detection techniques.

In Bucharest we do not have a proton accelerator and conditions to compete in the study of proton induced reactions. But it turns out we have good conditions to study α -induced reactions and reactions between light ions important in NA. Let me elaborate on that. IFIN-HH has now 3 tandem accelerators:

- an old, but fully refurbished, 9 MV FN tandem pelletron, which is used mostly for gamma-ray spectroscopy;
- a 3 MV tandetron, installed in 2012 and which works since mid 2013 for applications like Ion Beam Analyses, ion implantation and cross section measurements [1];
- a 1 MV tandetron completely dedicated to Accelerator mass Spectrometry, used for ${}^{14}\text{C}$ dating and other such applications (like geological dating).

Since the beginning of its operation we tested the capabilities of the 3 MV tandetron for direct measurements for nuclear astrophysics. The conditions necessary for this are: appropriate energy range, stability, diversity of projectiles, high currents. We tested all of the above and found the it will be competitive. The energies are given by the terminal voltage range which is $V=0.3 - 3.3$ MV. It was tested to be stable over weeks of operation. It has two ion sources: a duoplasmatron and a sputter source. Na, Cs and Li charge exchange are used preferentially. These allow a diversity of beams to be provided. Table 1 shows the intensities of the beams analyzed.

2.1. Nuclear Astrophysics Group (NAG)

An extra opportunity is provided by the ultra-low background laboratory the institute has in a salt mine located at about 100 km north of Bucharest-Magurele, in Slanic-Prahova [2]. We call it microBequerel. While at about 260 m below surface this is not a particularly deep mine, it has the property of being very low in natural radioactivity, due to a large distance from rocks and its compact walls. With a well shielded Ge detector a background reduction factor up to 4000 was obtained (relative to the surface background of the same unshielded detector).

Projectile	Intensity	Source
${}^1\text{H}^+$	$>25 \mu\text{A}$	duoplasmatron
${}^4\text{He}/{}^3\text{He}^+$	$> 3 \mu\text{A}$	
${}^{11}\text{B}^{3+}$	$>50 \text{e}\mu\text{A}$	sputter
${}^{12}\text{C}^{3+}$	$>80 \text{e}\mu\text{A}$	
${}^{16}\text{O}^{3+}$	$>80 \text{e}\mu\text{A}$	
${}^{28}\text{Si}^{3+}$	$>70 \text{e}\mu\text{A}$	
${}^{31}\text{P}^{3+}$	$>70 \text{e}\mu\text{A}$	
${}^{58}\text{Ni}^{3+}$	$>20 \text{e}\mu\text{A}$	
${}^{63}\text{Cu}^{2+}$	$>20 \text{e}\mu\text{A}$	
${}^{75}\text{As}^{2+}$	$>10 \text{e}\mu\text{A}$	
${}^{197}\text{Au}^{2+}$	$>80 \text{e}\mu\text{A}$	

Table 1. Beam intensities from the 3 MV tandetron [1].

We have, therefore, tested a procedure in which we irradiate targets in Magurele, then transfer them in Slanic and measure them [3]. Obviously this procedure will not work for cases where the resulting activity after irradiation has half-lives much shorter than the transfer time of about 2.5 hrs.

One case ideal for the test of the procedure we proposed together with colleagues from China (IMP Lanzhou and CIAE Beijing): the reaction $^{13}\text{C}+^{12}\text{C}$. The motivation of the experiment, the setup of 2014 and its preliminary results were presented at this school by one of our students and is included in this volume [4], please see it for details. You can see there pictures of the accelerator and of the salt mine. I will only mention here that only one reaction channel leads to radioactivity (one-proton evaporation), ^{24}Na which has $T_{1/2}=15.0$ h, excellent for the procedure we used: 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... With these we could reach (measurements in Sept.-Oct. 2014 and Oct. 2015) cross sections of the order of tens of picobarns, about 100 times more sensitive than any measurement done before. In the latter experiment we also measured prompt gamma-rays (as far down in projectile energy as we could) to assess the contribution of the other open reaction channels. Another condition, which did I not mention so far, is the availability of good detection devices. We have several high resolution, high efficiency HpGe detectors (100-120 % relative efficiency), many large Si detectors and we are building a large (80 cm diameter) reaction chamber. I mention that the tandems accelerators are internationally open facilities, with PAC meeting annually and are transnational access facilities under the ENSAR2 project.

2.2. Other activities in nuclear astrophysics

There are also groups in the Department of Nuclear Physics (DFN) of IFIN-HH using beams from the 9 MV tandem for nuclear astrophysics. They measured (α,γ) reactions at relatively low bombarding energies on medium mass targets, having in mind to obtain data for modeling the nucleosynthesis of the *p-nuclei*. One such example is presented at this school by Andreea Oprea [5]. Detailed measurements, down to energies close to the Gamow window, can provide data to determine optical potentials for α -particles at low energies and radiation strength functions. The experiments typically measure prompt or activation gamma-rays as the department is rich in gamma-ray detectors and in experience in using them. Experimental measurements are complemented by theory efforts to provide systematics of α -particle optical potentials at low and very low energies by Vlad and Marilena Avrigeanu of the same department (see for example [6] and references therein).

3. Indirect measurements at outside facilities

This type of measurements involve radioactive nuclear beams, as I said before, and they are planned or actually done at outside facilities. I will not talk generally about indirect methods in NA here, I was doing it at earlier editions of the school, they were discussed by prof. Carlos Bertulani a few days ago. I will only mention two of them, pursued by my NAG group.

3.1. Coulomb and nuclear breakup of ^9C at RIBF of RIKEN

We have proposed earlier to use breakup reactions to extract Asymptotic Normalization Coefficients and from there radiative proton-capture rates [7]. We were talking about nuclear breakup. Coulomb breakup was proposed long before and used as a reliable indirect method in NA [8, 9]. The current knowledge of the rate of the $^8\text{B}(p,\gamma)^9\text{C}$ reaction in stellar conditions is contradictory at best and there is no hope to determine it, now or ever, by other means than by indirect methods. This reaction gives a possible path to the hot *pp* chain *pp-IV* at high temperatures and away from it toward a rapid alpha process *rap I* at high temperatures and densities and therefore is important in understanding nucleosynthesis in super-massive hot stars in the early universe, including possible bypasses of the 3α -process. Our best hope at the determination of the astrophysical factor S_{18} at low energies is by using the $^9\text{C}\rightarrow^8\text{B}+p$ breakup. We proposed to use a combination of nuclear and Coulomb dissociation measurements using the SAMURAI spectrograph of RIBF at RIKEN (on a light target – Be or C and on a heavy target – Pb, respectively) at two energies (100 and 300 MeV/nucleon) to extract structure information which will allow to evaluate the radiative proton capture cross section at low energies and from there the reaction rate. We proposed an exclusive study of the reaction, which may allow a better

understanding of the reaction mechanism (proposal NP1412-SAMURAI29R1, approved by PAC Dec. 2014). The high probability of two-proton breakup ${}^9\text{C} \rightarrow {}^7\text{Be} + 2\text{p}$ for this projectile makes it a good case to learn about the complex reaction mechanisms involved. Such an understanding may allow for a better theoretical description of the reactions and more accurate calculations of the momentum and angular distributions, a crucial step in using indirect methods for nuclear astrophysics.

Not negligibly, the reaction proposed is the easiest among the p-HI experiments being planned at this point with SAMURAI and will be a good start for the use of the Si detector system in front of SAMURAI as it results in a smaller dynamical range and an easier particle identification and less kinematic focus. Part of the preparations for these experiment, actually for a whole set of proton breakup experiments proposed at SAMURAI was to build the detection system in front of the spectrograph which involves many channels (upward of 1024) and with the capability to measure energies on a very broad dynamic range (from 200 keV to 600 MeV). An approach based on ASICs was proposed, developed and tested at the HIMAC medical facility in Chiba, Japan. I do not detail that multi-year work here.

3.2. β -delayed proton decay with AstroBox2 at Texas A&M University

Last edition of the school I discussed the design of a new type of detector to measure β -delayed proton emission, using a detection scheme that involved the stopping of the p-emitting nuclei in the middle of a gas detector after their production and separation with the MARS recoil separator of the Cyclotron Institute at Texas A&M University. The β -delayed protons emitted produce ionization in gas and the resulting charges are directed and then amplified with very efficient and good resolution devices called micromegas. The detector was called Astrobox1 [10] and we have shown its use for measuring very low energy protons, as well as the connection between these measurements and the determination of astrophysical reaction rates for proton induced reaction rates dominated by resonances. Its main advantage over very the thin Si detectors (45-65 μm) we have used in the first stage of this project is that it is less sensitive to betas emitted always in the first stage of the decay, which gave a large continuous background in Si at low energies, exactly in the energy range of interest for us (protons of 150-500 keV). The sensitivity is down to around 10^{-4} (p-branching ratios). Since, we have worked, with our colleagues at CEA/IRFU Saclay, TAMU and CERN on an improved version of this detection scheme. The detector, dubbed Astrobox2, was built in this transcontinental collaboration and the first test measurements were done at the Cyclotron Institute, Texas A&M University, in College Station, TX in April 2015. The active part of the detector, the micromegas was built for us by a group at CERN, the inventors of such devices. The body of the detector was designed in Texas by dr. A. Saastamoinen. Its design and realization was actively pursued by us and by our collaborator from CEA/IRFU Saclay, France, dr. E. Pollacco. Schematically is shown in Figure 1. The main difference from AstroBox1 is that it does not have anymore a cylindrical symmetry (on an axis perpendicular to the beam), but is more appropriate to the geometry of the beam and its stopping in the gas of the detector. Another difference is that it has 29 separated pads and correspondingly 29 signals, compared with 3 (or 5) only for AstroBox1 (AB1).

The tests that were done, were:

- Off-beam tests using ${}^{55}\text{Fe}$ and ${}^{241}\text{Am}$ sources
- In-beam commissioning of the detector using a ${}^{25}\text{Si}$ radioactive beam separated by the MARS spectrometer. The radioactive specie we used, ${}^{25}\text{Si}$, is very appropriate for a test of a new proton detector, as it is a good, well known, β -delayed proton emitter with a large β -branching. It was produced at a reasonable rate from a primary beam of ${}^{28}\text{Si}$ at 40 MeV/nucleon on a ${}^{27}\text{Al}$ solid target. The result was actually a cocktail of secondary beams, a benefit for the identification of the beam in AB2.
- In-beam measurements for the ${}^{23}\text{Al}$ secondary beam, which is the main focus of the physics for these measurements.

The same scheme of measurements was used in 2012 on a test of AB1. The first two parts of the tests went very well, and the commissioning of the AB2 detector was a success. So appeared to be the

last measurement, for which we reserved the last 4 days of the experiment. The primary beam of ^{24}Mg at 45 MeV/nucleon was delivered successfully to us on Friday April 24, and the next day the secondary beam of ^{23}Al was selected and was stopped in the middle of the AB2. The data need still be fully analyzed to see if the reconstruction of all signals from adding the adjacent pads improved the statistics to the point we need.

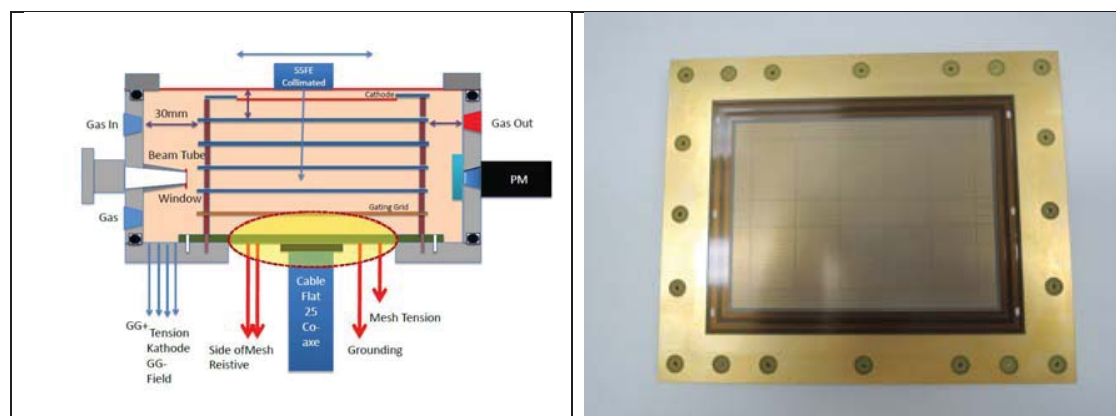


Figure 1. AstroBox2: left - schematic view of the detector, parallel to the beam entering from left; right - photo of the micromegas plate.

3.3. Theory for indirect methods in NA

We have a long-term program to understand and describe nucleus-nucleus collisions in terms of one interaction potential, the optical model potential (OMP). A good understanding of all phenomena occurring in the elastic nucleus-nucleus scattering, which are used typically to extract OMP, and the interpretation of the origin of different aspects, including the well know potential ambiguities, are of crucial importance for finding and justifying the procedures used for predicting nucleus-nucleus OMP in the era of radioactive nuclear beams (RNB), including ours based on double folding [11]. The reliability of these potentials is crucial in the correct description of a number of reactions involving RNBs, from elastic to transfer, to breakup, at energies ranging from a few to a few hundred MeV/nucleon. Of particular interest for us is to support the absolute values of the calculated cross sections for reactions used in indirect methods for nuclear astrophysics [13]. In this framework, we paid and pay particular attention to obtain OMP using double folding and to finding systematics for the re-normalization coefficients that appear as needed in quasi-all cases. It is extremely important for the use of indirect methods to be able to obtain and rightfully claim good absolute values for the calculated cross sections for various phenomena (including ^9C breakup, e.g.), see Refs. 12-14 for the most recent results.

4. ELI-NP

The most important and the most notable news from IFIN-HH in the last 3 years is ELI-NP. This is a large European project being built by our institute, in our institute and is designed to be an independent European institution in a few years. It consists of two 10 PW lasers and a gamma-beam system capable of delivering brilliant and mono-energetic gamma beams up to 19-20 MeV. These powerful lasers will make possible a nuclear physics program that has many potentially unique capabilities. Is being described in the talk by dr. O. Tesileanu here, including its program in nuclear astrophysics, which is developed in collaboration with scientists from Europe and the whole world, including many from LNS Catania. I will list here only one idea that may not have been included in that talk. It is expected that at ELI-NP stellar plasma conditions will be produced for long enough

periods of time to have nuclear reactions in equilibrium at large temperatures T . There will be many problems, like how to realize those stellar plasmas, how to characterize them, how to obtain and measure the signals, but among other things, they may provide the unique opportunity to measure reaction rates for capture reactions on excited states and without electron screening [15]. Impossible to realize otherwise in any current laboratory!

And, by the way: one of the best things for the future users of ELI-NP is that there is already a 1 PW laser running on our campus, not in IFIN-HH, but in the laser institute nearby (INFLPR).

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