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Project title: “Direct measurements of Nuclear Astrophysics at IFIN-HH”

NUCASTRO2

Intermediate Report December 2017

Masuratori si analiza preliminara a datelor din reactii induse de particule alfa de joasa energie

Raport de faza preliminar pentru experimentul ^{64}Zn+alfa E= 4 – 9 MeV

Experimental study of the ^{64}Zn+α reaction in the Gamow region

As it was proved by tests and past experiments the 3 MV TANDETRON accelerator of IFIN-HH have demonstrated its capabilities for direct measurements for nuclear astrophysics. Tests have proven that it has appropriate energy range, stability, high currents and it is competitive for ^{4}He and light ion beams [1]. The other facility that our institute benefits of is the ultra-low background laboratory placed in a salt mine located at about 120 km North of Bucharest-Măgurele, in Slănic-Prahova [2], the microBequerel laboratory. This is not a particularly deep mine, being at about 209 m (estimated to 560 m water equivalent) below surface, but due to a large distance of caves from rocks and to the high purity of the salt it has the property of having a very low natural radioactivity. Measurements using a shielded Ge detector have shown that the background reduction factor is up to 4000 (relative to the surface background of the same unshielded detector).

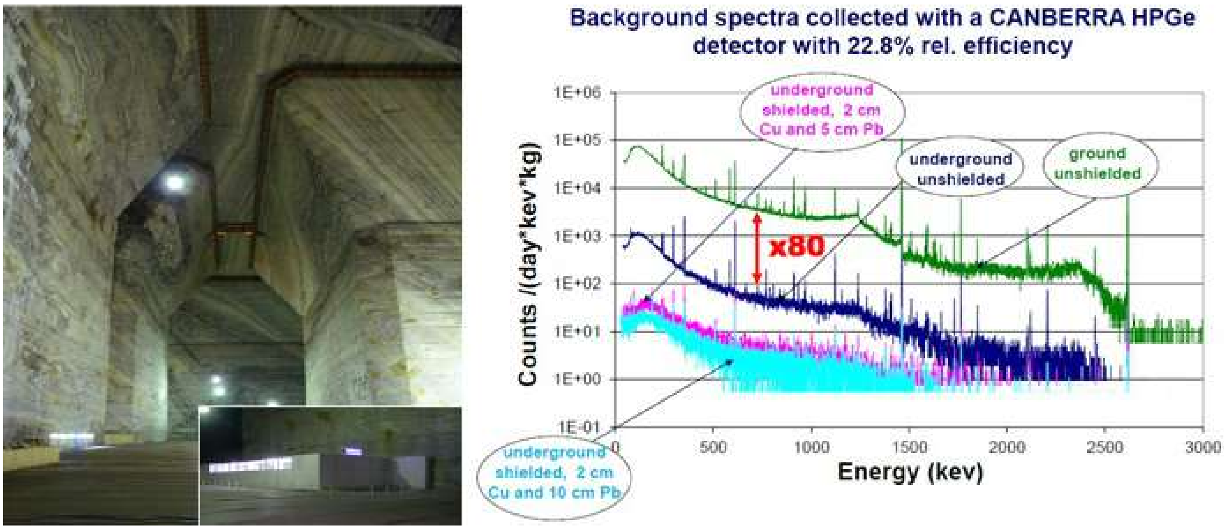

Figure 1. Background from the salt mine (μBq laboratory) [2].

We have, therefore, tested in Oct. 2014 and Oct. 2015 a procedure in which we irradiate targets in Măgurele, then transfer them in Slănic and measure them [3, 4]. 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. An ideal case for the test of this procedure was proposed together with colleagues from China (IMP Lanzhou and CIAE Beijing): the reaction $^{13}C+^{12}C$. Only one reaction channel leads to radioactivity, one-proton evaporation $^{12}C(^{13}C,p)$, producing ^{24}Na which has $T_{1/2}$=15.0 h, excellent for the procedure we used: one day of irradiation, transfer to Slănic in 2.5 hours 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 Oct. 2015 and 2016) down to cross sections of the order of 90 pb, about 100 times more sensitive than any measurement done before for this reaction. These experiments were for the first time reaching into Gamow window for the reaction in question.

We concluded that the laboratory can be competitive for direct nuclear astrophysics measurements induced by alpha particles and light ions. We used these findings and strengthened them on cases that can use this combination of facilities. For now, we planned to continue a program that goes on two distinct lines:

- Continue the study of reactions between light ions like ^{12}C and ^{16}O down into the Gamow window or as close as possible to it;
- Proceed with the program using α-beams to measure α-induced reactions on proton-rich nuclei. Selection at this point was being done for reactions that produce activations that are long enough for the targets to be transferred to Slănic.

$^{64}Zn(\alpha,\gamma)^{68}Ge$ fusion reaction

The nucleosynthesis of elements heavier than iron is particular because their synthesis requires energy so their production cannot be the source that powers a star. Therefore, their existence in nature must be explained by other process than He-burning, C-, O- or Si-burning in massive stars. Most of the heavy elements are produced through neutron capture reactions. There are two main processes of neutron capture: s- and r- processes. However, on the proton-rich side of the valley of nuclear stability there are almost three dozen of heavy stable isotopes that cannot be produced by these two processes. These are the p-nuclei which have very low elemental abundances (~1%). Information about the abundance of p-isotopes comes from the Solar System. And since the performance of telescopes does not allow the identification of p-isotopes in stellar spectra the p-process, nucleosynthesis models try to reproduce the p-isotope abundances from the Solar System.

Despite all efforts, there are differences between the observed and calculated p-isotope abundances. To reduce the discrepancies several processes are considered: υ-, υp-, rp-, pn-, which are sub-processes of the p-process. One process that is also able to produce proton-rich isotopes is the γ-process. This process occurs through γ-induced reactions on heavy isotopes. In stellar environment (where temperatures are high) the high energy wing of the Planck distribution is energetic enough to remove neutrons from heavy isotopes. p-isotopes are produced through consecutive (γ, n) reactions which lead the material to proton-rich region. In this way isotopes become more and more neutron-deficient and charged particles emitting (γ, p) and (γ, α) reactions start to play an important role and influence the p-isotopes abundances. γ-induced reactions take place at high temperatures and different explosive scenarios are thought for the γ-process. The most intensively studied is the O/Ne layer of core collapse supernovae, but type Ia supernovae are also considered.

For γ-process modelling the astrophysical conditions must be known. Simulations show that the information about the seed isotope abundance and also about the conditions of explosion's spatial and temporal variation of density and temperature are essential. Equally important is the nuclear physics input. A full γ-process network calculation involves thousands of reactions, the rate of which must be known for a reliable calculation. Most of the reactions take place on radioactive nuclei, therefore it is not surprising that experimental data are very scarce and the models have to rely on theoretical reaction rates obtained typically from the Hauser-Feshbach statistical model. The fact that the γ-process models fail to reproduce the observed p-isotope abundances can be related to the possibly incorrect reaction rates from theory.

The Gamow window for the ^{64}Zn(α, γ)^{68}Ge reaction is between 4 and 6.5 MeV (the γ-process temperature is around 3 GK) and for this energy range only two of the channels are open: ^{64}Zn (α, γ)^{68}Ge, ^{64}Zn (α, p)^{67}Ga and the third one ^{64}Zn (α, n)^{67}Ge has a threshold at 9.5 MeV. Therefore, we have to take into account that the experimental study of γ-process related reactions is of high importance in order to provide direct data for the γ-process networks and to check the reliability of statistical model calculations we decided to also study the ^{64}Zn (α, γ)^{68}Ge reaction [5,6,7,8].

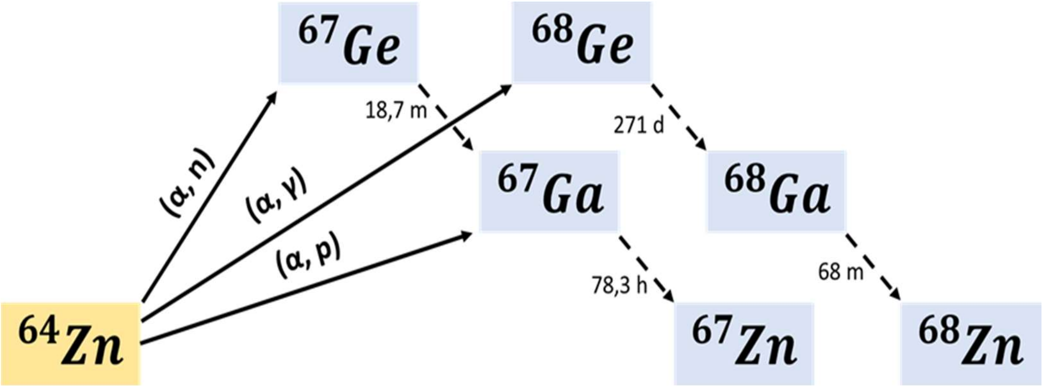

Figure 2. Open channels for the reaction.

Until now we studied ^{64}Zn (α, p)^{67}Ga fusion reaction that was approved by the Proposal Advisory Committee. During the experiment we irradiated natural zinc targets by alpha beam with energies in the laboratory frame between 5.4-8 MeV with steps of 0.2 and 0.25 MeV. The thick target yield for $^{64}Zn(\alpha,p)^{57}Ga$ reaction was determined through measurements of the γ-ray yield following the decay of ^{67}Ga ($T_{1/2}$=78.28 h) in two laboratories: microBequerel and NAG (Nuclear Astrophysics Group), where the gamma rays (184.6, 209.0, 300.2 and 393.5 keV) were detected with HPGe detectors with relative efficiency of 120% and 100% respectively. A sample spectrum is shown in Figure 3.

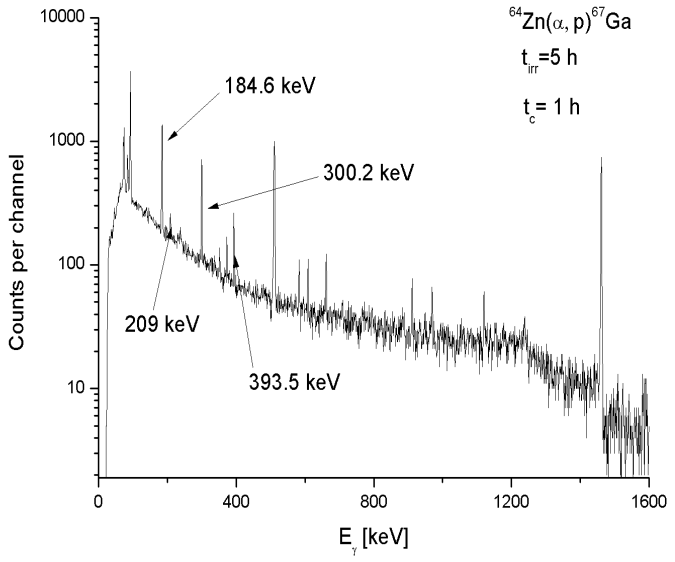

Figure 3. Gamma rays from activation measurements.

Detectors where calibrated using sources with well-known activities like:^{152}Eu, ^{133}Ba, ^{60}Co. The calibration curve for one of the NAG detectors used is shown below, in Figure 4.

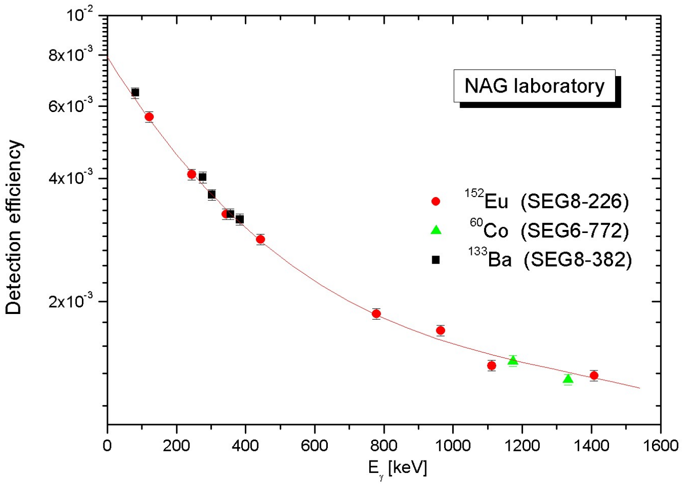

Figure 4. Detection efficiency calibration curve.

Further, the $^{64}Zn(\alpha,p)^{57}Ga$ cross section have been determined from the extracted thick-target yield Y(E):

$$Y(E) = \int_0^E \sigma(E)\frac{dx}{dE}\frac{N_A}{A_t}dE \tag{1}$$

Experimental cross sections were extracted by differentiation (using the thick target method):

$$\sigma(\tilde{E}) = \frac{Y\,(E + \Delta E) - Y\,(E)}{n_t} \cdot 10^{24} b \qquad (2)$$

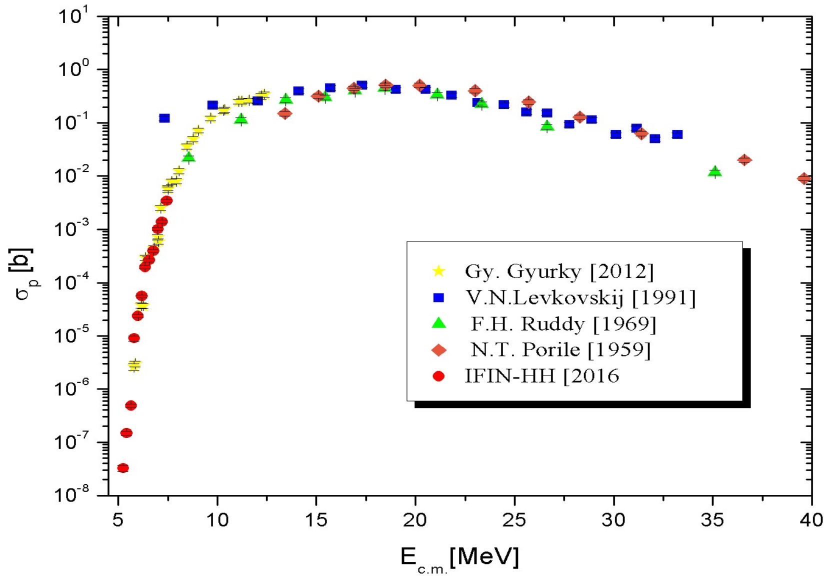

Figure 5. Preliminary results of experimental cross section for ^{64}Zn (α, p)^{67}Ga in comparison with previous experiments [5, 6, 7].

The preliminary results obtained from the de-activation measurements are presented in Figure 5 (proton cross section) and Figure 6 (astrophysical factor). Comparable results with previous experiments and theoretical calculations have been obtained.

$$S(E) = \sigma(E) * E * \exp(2\mu\eta) \qquad (3)$$

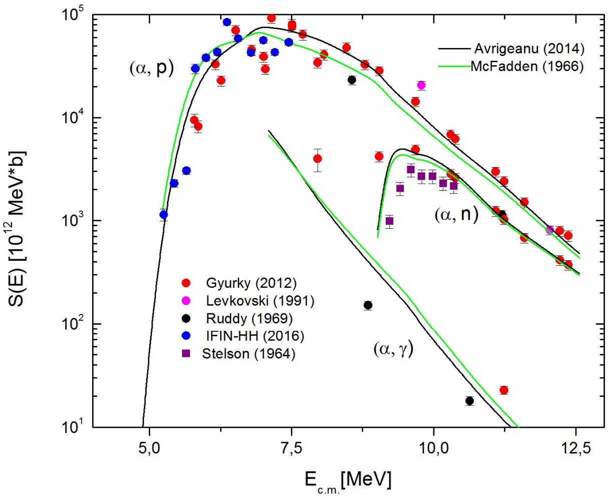

Figure 6. The astrophysical S(E) factor of experimental data obtained from ^{64}Zn (α, p)^{67}Ga, ^{64}Zn (α, n)^{67}Ge, ^{64}Zn (α, γ)^{68}Ge reaction channels in comparison with theoretical results [9, 10].

Furthermore, in order to complete the program, in October this year we forwarded the proposal *Experimental study of the* $^{64}Zn(\alpha,\gamma)^{68}Ge$ *fusion reaction* to the PAC (Program Advisory Committee) of IFIN-HH. The experiment was approved and scheduled to take place in November next year. During the experiment we plan to irradiate natural zinc targets with energies between 7.4 and 8.4 MeV with steps of 0.2 MeV. For the ^{64}Zn $(\alpha, \gamma)^{68}$Ge ($T_{1/2}$ =271 d) reaction we plan to do de-activation measurements in microBequerel and NAG laboratories. To increase the sensitivity, we also want to use a new beta-gamma coincidence installation we built this year: two HPGe detectors with relative efficiencies of 100% placed one in front of the other and a plastic scintillator for $\beta-\gamma$ coincidences (BEGA, to be described below). In addition, prompt in-beam gamma-rays will be detected with two HPGe detectors in close geometry for as long as the reaction cross section will be sufficiently large for those gammas to be extracted from the background of the target hall.

The total required beam time was 9 days as follows:

- in the first 4 days we plan to irradiate 4 targets at different energies (8.4 and 8.2 MeV) and measure them as follows: in the first day we irradiate 2 targets at 8.4 MeV which will be measured, one at the salt mine and the other at IFIN; in the second day we will irradiate at 8.2 MeV and wait almost 24 days for the first target to be measured until we measure the second target.
- after approximately one month we plan to irradiate the following 4 targets (8 and 7.8 MeV) and to repeat this procedure for all targets.

The BEGA detection system

This year we designed and built in collaboration with the Romanian representative of Canberra Ltd. a compact and powerful system for beta-gamma coincidences. It is meant to do de-activation measurement for cases where the activities are from isotopes that have lifetimes too short to make possible the transport in the salt mine at Slănic. Therefore, the background reduction is made with beta-gamma coincidences. In addition we require an exact and easily reproducible geometry, to avoid lengthy and uncertain calibrations. A sketch of the BEGA system is presented in Figure 7. It is financed from this project.

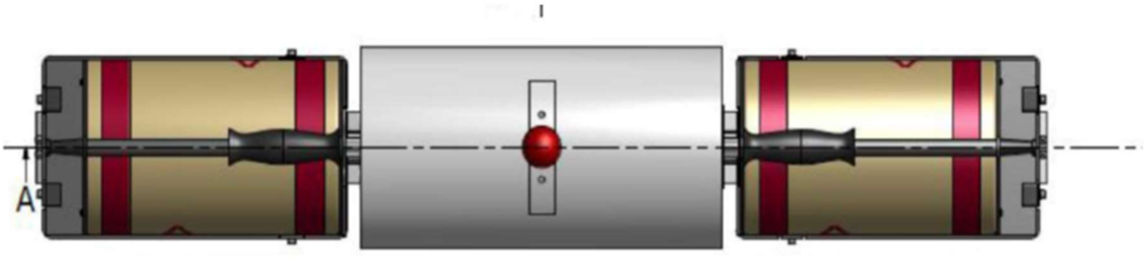

Figure 7. BEGA: the beta-gamma coincidence system

In conception BEGA is simple:

- a plastic scintillator with a 20 mm x 20 mm x 2 mm slot in the middle where the activated target will be positioned. It will assure a 4π coverage and therefore, a maximum detection efficiency.

- Two HPGe detectors on each side of the target, in closest possible geometry. Space is left for metallic foils (Cu and Sn) to cut low Z X-rays.
- A Pb shield wrapping all 3 detectors.
- A table on which the system in mount that will assure a precise geometry and easy handling.

The system was designed this year, is being built, and will be delivered in December. Tests will be made early in 2018 and will be ready for use in April 2018 with the occasion of the ChETEC training school that our group is organizing (April 10-20, in Magurele). ChETEC (Chemical Elements as Tracers of the Evolution of Cosmos) is a COST Action (http://www.cost.eu) aiming to increase networking of specialists in nuclear astrophysics, star dynamics, nucleosynthesis and observational astronomy – http://chetec.eu. Participants are from 29 countries. The Project Director was a co-proposer. It was approved by the European program COST in November 2016 and was started in March 2017. The training school at IFIN-HH was approved in the fall of this year, with the following declared agenda (see website: http://www.nipne.ro/indico/conferenceDisplay.py?confId=354):

"*IFIN-HH of Bucharest-Magurele, Romania will host a ChETEC training school in nuclear astrophysics of 11 days duration, consisting in classes and hands-on activities:*

1. *In a target laboratory*
2. *Performing an experiment at the 3 MV tandetron (7 days around the clock)*
3. *Gamma-ray measurements at the 9 MV tandem and the ROSPHERE array*
4. *De-activation measurements in an underground laboratory microBequerel in the Slănic-Prahova salt mine.*

Local and invited trainers will lead the participants during the school that will cover most types of activities a physicist engaged in nuclear physics for astrophysics will have to go through, in particular those engaged in direct measurements for nuclear astrophysics.

The trainees:

- a. *will attend introductory classes*
- b. *will man the experiment round the clock,*
- c. *will make the experimental arrangement,*
- d. *will handle the DAQ system,*
- e. *will collect and*
- f. *will analyze on/offline data (prompt and de-activation gamma-rays).*

The activities of this school are particularly related to those afforded in the WG1 (Nuclear data for astrophysics: needs, coordination and dissemination) of the ChETEC COST Action. The intended level is PhD student and early post-doc (up to 8-years after PhD). We aim to have 15 students from abroad and 6 locals."

We will report on this training school results in next year's report.

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Consideram ca obiectivele fazei au fost pe deplin indeplinite.
Director de proiect,
Dr. Livius Trache