STUDYING STARS FROM THE DEEP UNDERGROUND: THE LUNA EXPERIMENT AND THE CASE OF ^{13}C(α,n)^{16}O REACTION

László Csedreki[1] **and Giovanni Francesco Ciani**[2] – DOI: https://doi.org/10.1051/epn/2023505
[1] HUN-REN Institute for Nuclear Research (ATOMKI), Debrecen, Hungary
[2] INFN- Bari, Italy.

Understanding the stellar evolution and the origin of chemical elements are the main goals of Nuclear Astrophysics. In the last century, many collaborations worked to develop experiments and accelerators to study in Earth laboratories the main nuclear processes taking place in stars at their relevant temperature. As an example, we present the measurement of the ^{13}C(α,n)^{16}O reaction performed by the LUNA collaboration.

Production of chemical elements in the Universe

Everything around us, from our body to the entire Universe, is made by all the chemical elements of the periodic table. Their abundance, the percentage of presence of different nuclei, varies by several orders of magnitude. For example, in Fig. 1 the abundance of chemical elements is shown, normalised with respect to the silicon, as a function of atomic number in the Solar System. Light elements are the most abundant (Hydrogen and Helium are the 98% of the Solar System) and their dependence is almost a decreasing exponential, with 13 orders of magnitude difference for the heaviest elements.

Elements are synthetised in astrophysical environments: the lightest and most abundant elements, hydrogen and Helium, are created in the Big Bang Nucleosynthesis (BBN). The valley for Li, Be and B comes mainly in cosmic-ray induced nuclear reactions in the interstellar medium. All other nuclei, from carbon to uranium, were born inside Stars at the different stages of Stellar evolution. Moving from carbon to heavier elements along the abundance curve, a reduction can be observed, with exception of an evident peak around iron. These elements are produced in a sequence of fusion reactions towards higher atomic numbers [1]. Above the isotopes of the iron group, nucleosynthesis cannot occur by fusion reactions between charged particles for two reasons. Firstly, the reactions become endothermic and that means that they cannot happen spontaneously. Moreover, with the increasing atomic number, the electric repulsion increases, thus at typical stellar temperature, well below the Coulomb barrier, the reaction cross section becomes extremely low. Of course, neutral particles, as neutrons, are not affected by repulsive Coulomb forces. According to recent knowledge, heavy element synthesis is based on neutron capture processes. There are *s(slow)*- and *r(rapid)*- processes. If the produced radioactive nuclei can decay before the next neutron capture, it is a slow process. In general, it takes place in an environment with a low neutron density in AGB stars. On the other side, if a daughter nucleus can capture more than one neutron before decaying, it is a rapid process that takes place in a stellar environment with high neutron density such as stellar neutron mergers. In Fig. 1 nuclides synthetised by r- and s process are indicated with blue and green curves, respectively. Only a minority of nuclei beyond iron is synthetized by the so-called p-process that involves a proton capture (red dots in Fig. 1).

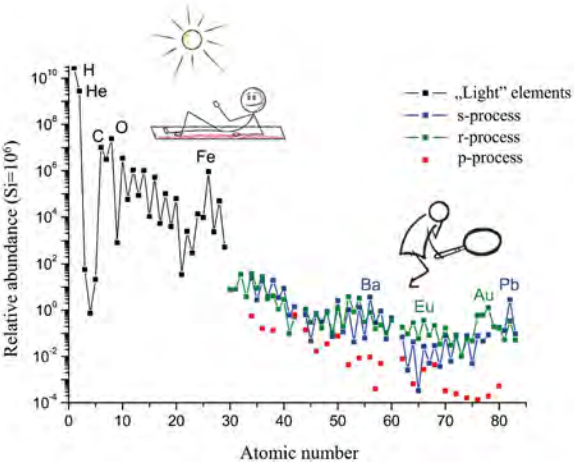
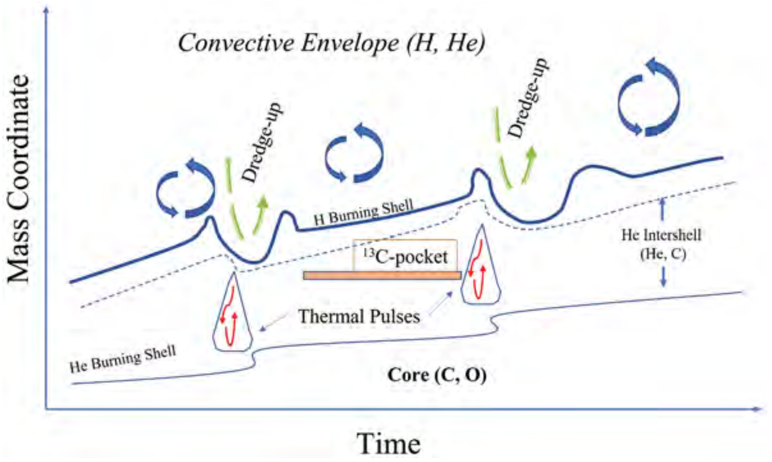


FIG. 1: Abundance of chemical elements in our Solar System (the contributions of the different processes of heavy element nucleosynthesis are labeled separately).



▲ **FIG. 2:** Temporal evolution of the different layers during the thermally pulsing AGB phase. The convective regions generated by two subsequent thermal pulses are also shown.

The study of the neutron sources and the origin of astrophysical s-processes

As mentioned before, we know that elements beyond iron are produced in the slow and rapid processes. Where do neutrons come from? For the s-process, it is well known that they are emitted from charge particle fusion reactions taking place during complex convective motion in stars of the Asymptotic Giant Branch which are stars in an advanced stage of their life. In Fig. 2. the internal structure of an AGB star is shown. Helium-burning takes place in the He burning shell covering the carbon-oxygen core of AGB stars. The helium is reproduced continuously in the hydrogen-burning phase in a separated shell and at a critical density the helium-burning is ignited. The energy released in this process causes the expansion of the star. When the helium runs out, the star contracts and the hydrogen-burning phase continues. The timescale of such an event is a couple of decades, which is repeated after some thousands of years. The material of the AGB star is mixed during the expansion (labeled as Dredge-up in the Figure) and the hydrogen from the convective envelope transported in deeper layers is captured on ^{12}C nuclides, which produce ^{13}N. Finally, the beta-decay of ^{13}N leads to ^{13}C nuclides forming the so-called ^{13}C-pocket. With the subsequent dredge up phase, Helium enters in the pocket that causes the ^{13}C(α,n)^{16}O reaction emitting neutrons that later are captured by the s-process nuclides. Therefore, knowledge of the ^{13}C(α,n)^{16}O cross section at the relevant energy region (Gamow-window, see box) allows for a better understanding of the synthesis of heavy elements.

In the last decades, several experiments have been performed in surface laboratories all around the world, but all of them were limited by the neutron background coming from secondary cosmic rays. It caused high uncertainties that did not allow for extrapolating data towards low energy and reaching the requested precision for stellar models.

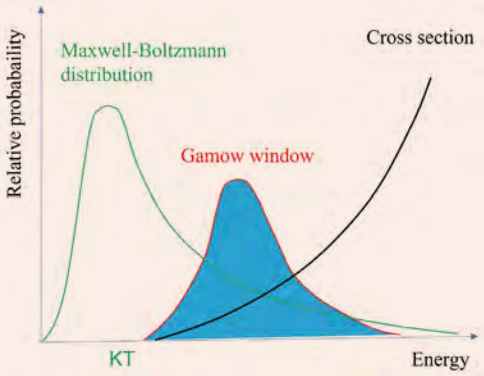
The LUNA experiment at Gran Sasso National Laboratory

In 2015, the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration decided to run the race towards the ^{13}C(α,n)^{16}O measurement, taking advantage from the intense alpha beam provided by the LUNA400 accelerator, from the neutron background reduction by three orders of magnitude of LNGS with respect to surface laboratories. The participation of LNGS to an international network allowed for building synergies with surface laboratories all over the world, such as ATOMKI (Debrecen, Hungary) and HZDR (Dresden, Germany) to collect experience in all the fields necessary to keep under control all the critical aspects of the measurement: the target production, the design and characterisation of the detection setup, data taking, data analysis for R-matrix extrapolation to lower energies and research for possible astrophysical consequence. All the steps are summarised in Fig. 3.

The four main aspects, which basically determine the available precision of the cross-section measurements are the intensity of the ion beam, the target properties, the detection efficiency of the neutrons and neutron background of the experimental apparatus. In particular, the ideal situation demands to have, together with the very intense alpha beam provided by the LUNA400 accelerator, targets with a very high density of ^{13}C nuclei. Therefore, targets were produced at ATOMKI by evaporation of 99% enriched ^{13}C powder on tantalum disks. The composition of the target was periodically checked using dedicated

GAMOW-WINDOW

The main challenge of nuclear astrophysics is to provide precise information of nuclear reactions mainly in a relevant energy region: the so-called Gamow-window, where the fusion most likely occurs. Its value (blue area) depends on the stellar temperature and the interacting particle. This comes from the convolution of two functions: the Maxwell-Boltzmann distribution (green line) that model the energy distribution of stellar gas, and the probability to overcome the Coulomb barrier (black curve). For the 13C(α,n)16O in an environment of T=0.9GK, the Gamow window is between 130 and 240 keV and the LUNA experiment successfully reached this energy range for the first time ever in the measurement described here.



techniques, that we do not describe here but those interested can find it in [2]. A huge work was done also for the research of the best setup to use in terms of material and design. ^{3}He counters have been used because of their intrinsic high detection efficiency. In order to maximise the geometrical efficiency, 18 counters have been arranged in two concentric rings (6 and 12 in the inner outer ring, respectively) in order to cover a 4π angle around the target. Another peculiarity was that the LUNA collaboration chose stainless steel counters instead of typical aluminum ones to reduce the radioactivity of the material in the setup and consequently its intrinsic background. A devoted paper on the setup construction was published in 2021 [3]. Because ^{3}He counters are sensitive to slow neutrons (E_n = 25 neV) and neutrons emitted by the reaction have energy E_n > 2.5 MeV, counters were inserted in a polyethylene moderator that slowed down neutrons. The detection efficiency in these conditions was estimated around 35% thanks to complementary measurements at particle accelerator of ATOMKI and neutron source measurement at University of Naples, Italy. Combining the background reduction of LNGS, the intense alpha beam provided by LUNA-400 accelerator and the experimental efforts mentioned above, in a three year experimental campaign, the LUNA collaboration measured the $^{13}C(\alpha,n)^{16}O$ cross section directly inside their s-process Gamow window for the first time, reaching an overall uncertainties lower than 20%. Based on the calculated reaction rate from the theoretical extrapolation of the measured cross-section data, the astrophysical impact has been also estimated. Sizeable variations of some isotopes were found, whose production is influenced by the activation of close-by branching points that are sensitive to the neutron density, in particular, the two radioactive nuclei ^{60}Fe and ^{205}Pb, as well as ^{152}Gd [4]. The unprecedented results obtained by the LUNA collaboration have been confirmed by another measurement performed at China Jinping Underground Laboratory by the JUNA collaboration [5]. Although the community recognised the importance of this results, there is still a lot to do to improve the knowledge of s-process. Future prospect is to perform measurements in a wide energy range with angular distribution measurements completed with multi-channel R-matrix calculations considering the other reaction channels of $^{13}C+\alpha$. Stay tuned!

About the authors

László Csedreki is a Senior Research Fellow of the HUN-REN Institute for Nuclear Research (ATOMKI), Hungary. He studies low-energy nuclear astrophysics reactions at particle accelerators. He spent 4 years as a Postdoc at the LNGS laboratory, Italy. csedreki@atomki.hu

Giovanni Francesco Ciani is a Staff Technologist at INFN- Bari, Italy. His main research topics are low-energy nuclear astrophysics and detector development. giovanni.ciani@ba.infn.it

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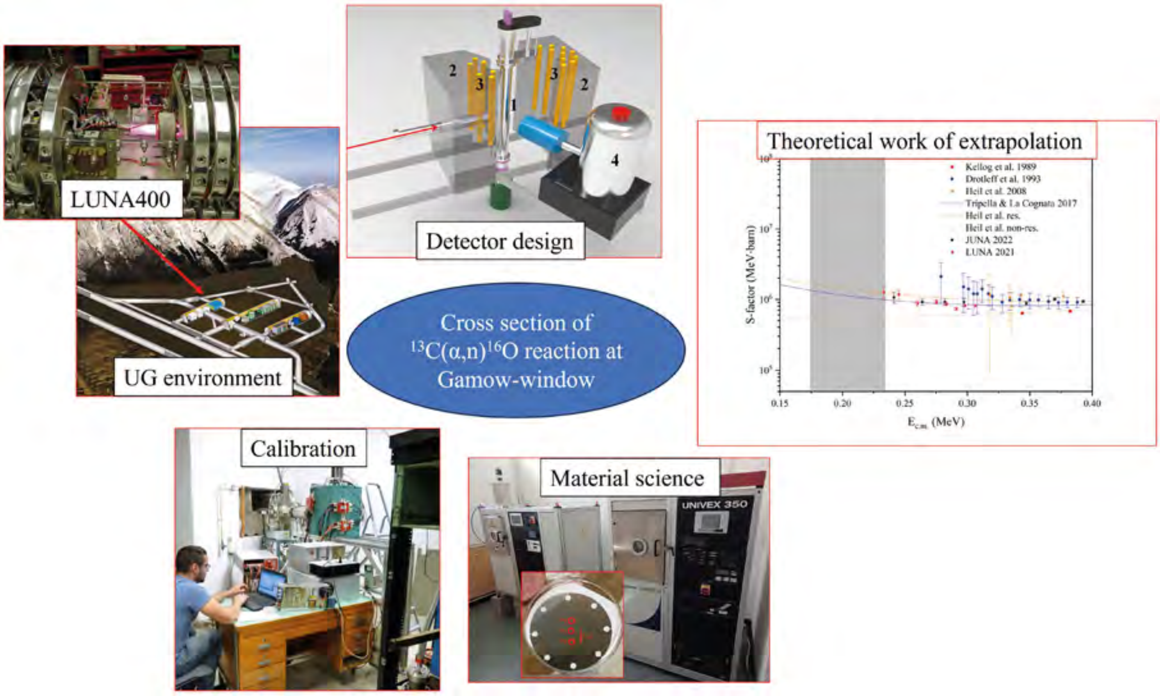

FIG. 3: Flow-chart of the $^{13}C(\alpha,n)^{16}O$ reaction measurement represents the complexity of an Nuclear Astrophysics experiment.