Project closing report for postdoctoral project

PD-129060-Experiments related to the $^{13}C(\alpha,n)^{16}O$ astrophysical key reaction

01.10.2018-30.09.2023

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1. Scope of the project

The main goals of the nuclear astrophysics are to understand the stellar evolution and the production of the chemical elements in our Universe via the study of the relevant nuclear reactions. To understand the different astrophysical processes, precise knowledge of nuclear reactions (total and differential nuclear cross section, nuclear structure, etc.) at the astrophysically relevant temperature region (Gamow-window) are needed. In most cases, the reaction cross section is too low at these temperatures to be measured directly, thus high precision measurement of nuclear reactions in a wide energy region and the extrapolation of data towards the low energy regime are required.

The main goals of the OTKA/NKFIH (129060) project were to study alpha and proton induced reactions on carbon isotopes connected to the nucleosynthesis of heavy element and the astrophysical CNO cycle.

Half of the chemical elements heavier than iron in our Universe are produced in the so-called astrophysical s-process through sequences of neutron capture reactions. Spectroscopic observations combined with stellar models support the $^{13}C(\alpha,n)^{16}O$ reaction as the neutron source for the main components of s-process in Thermally Pulsing Low-mass Asymptotic Giant Branch (TP AGB) stars. Moreover, the $^{13}C(\alpha,n)^{16}O$ was identified also as a neutron source for the i-process supposedly responsible for the characteristic abundance distribution in Carbon Enhanced Metal Poor (CEMP) stars. To understand the observed chemical abundances in TP-AGB, complex study of stellar structure, composition and mixing phenomena supported by precise reaction rates (derives from reaction cross sections in the relevant astrophysical energy window) are crucial. Several experiments have been devoted to investigate the behaviour of the $^{13}C(\alpha,n)^{16}O$ reaction using direct and indirect methods. However, the extrapolation of the astrophysical *S(E)*-factor of this reaction into its s-process Gamow window ($E_{c.m.}$=140-230 keV) is challenging due to the contested effect of a resonance in ^{17}O located near the threshold (E_α=0 keV) and high uncertainties of the experimental data in the low-energy region.

Another important aspect of nuclear reactions at carbon isotopes is connected to the astrophysical carbon-nitrogen-oxygen (CNO) cycle. H burning via the CNO cycle is the main nuclear energy source in massive stars during the main sequence phase and in stars in more advanced stages, i.e., AGB stars and red giant branch (RGB). Thus, the measured isotopic rates at stellar surface provides indication of mixing process at deeper layers (such as convection, magnetic buoyancy, rotation, etc.). The $^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ reaction is part of the CNO cycle and they determine the abundance of carbon isotope in the hydrogen-burning region. Thus, the $^{12}C/^{13}C$ isotopic ratio measured at the surface spectrum of a star can be used as a fingerprint in the investigation of stellar evolution. Another aspect of the study of $^{12}C(p,\gamma)^{13}N$

reaction is connected to the better estimate of neutrino yields given by the Standard Solar model (SSM), which so far provides the best description of our Sun. To be better constrained the above described phenomena, the cross section of $^{12,13}C(p,\gamma)^{13,14}N$ reactions have to be extrapolated in the $E_{c.m.}$=20-70 keV energy region.

2. Experimental apparatus

To properly constrain the nuclear reaction rate of a given nuclear reaction in its Gamow window, experimental cross-section data with well-constrained experimental uncertainties, such as target properties, detection efficiency of the reaction products, effective suppression of environmental background and high intensity ion beam are crucial. To provide these circumstances, complex experimental apparatus based on accelerator laboratories at surface and underground are needed.

Measurements of target characterisation and reaction cross-section were performed at the 2.0 MV Medium-Current Plus Tandetron Accelerator at ATOMKI, Debrecen, Hungary. Moreover, dedicated measurement of neutron detection efficiency for the study of $^{13}C(\alpha,n)^{16}O$ reaction was performed at the Van de Graaff accelerator of ATOMKI. Beside these measurements, targets for the different campaigns introduced in this report were produced with electron beam evaporation technique at the ATOMKI.

To constrain the cross-section extrapolation at the Gamow-windows of the different reactions, low-energy measurements at the LUNA400 accelerator in the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy were performed. The accelerator is operated by the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration (involved Italian Institutes, ATOMKI and Felsenkeller Laboratory). The LNGS Underground Laboratory provides an ideal environment to establish the direct measurement of this reaction at low energy thanks to the reduction of neutron background with 3 orders of magnitude compared with other facilities on the Earth surface. The cross section measurement of $^{13}C(\alpha,n)^{16}O$ reaction were implemented in the $E_{\alpha,lab}$=300-400 keV energy range . Moreover, the $^{12,13}C(p,\gamma)^{13,14}N$ reactions were measured also at underground environment in the $E_{c.m.}$=60-370 keV region.

Measurements of total and differential cross-section related to the $^{12}C(p,\gamma)^{13}N$ reaction, partially were performed at the 5MV Pelletron accelerator of Felsenkeller Laboratory provided molecular H2+ beam with proton energies ranging between E_p = 350 and 670 keV. The laboratory is located in a shallow underground tunnel. Thanks to the 45 m rock, which covering the accelerator facility, muon and neutron flux are suppressed with a factor of 40 and 180, respectively, compared with values at surface.

3. Results and Discussion

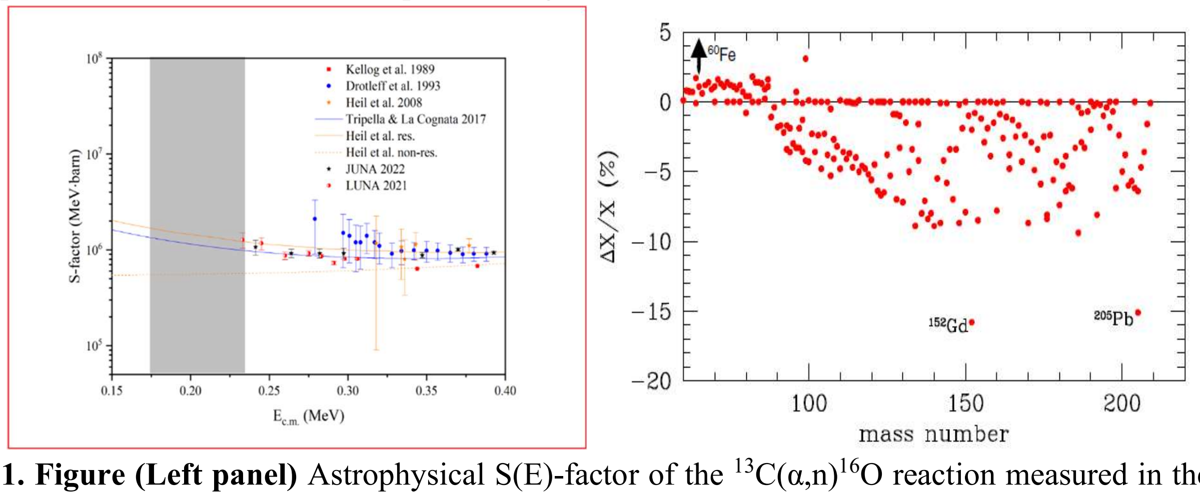
a. The $^{13}C(\alpha,n)^{16}O$ reaction

The four main aspects, which basically determine the available precision of the cross-section measurement 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 enriched 99% ^{13}C powder on tantalum disks. The composition of the target was periodically checked using devoted techniques such as the Nuclear Resonant Reaction Analysis (NRRA) and the Gamma-shape analysis, which allowed us to monitor target degradation effect on an in-situ way during the data taking. The technical details are published in **G. F. Ciani, L. Csedreki et al. 2020** paper **[1]**.

A dedicated setup was developed for the cross section measurement of $^{13}C(\alpha,n)^{16}O$ reaction. The neutron yields were detected in 18 ^{3}He gas filled proportional counters formed an array, so-called LUNA neutron array. To maximize 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 of the setup was that stainless steel housing of the counters instead of typical aluminum ones was used. This reduced the radioactivity of the material in the setup and consequently its intrinsic background. 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. A devoted paper on the setup construction and characterisation of its properties was published in **L. Csedreki et al. 2021 [2]**.

Combining the background reduction of LNGS, the intense alpha beam provided by LUNA-400 accelerator and the experimental efforts mentioned above, the $^{13}C(\alpha,n)^{16}O$ cross section was measured directly inside their s-process Gamow window for the first time, reaching an overall uncertainties lower than 20%. The new experimental data with a comparison of previous data are shown in left panel of Figure 2.



1. Figure (Left panel) Astrophysical S(E)-factor of the $^{13}C(\alpha,n)^{16}O$ reaction measured in the framework of the project (red cycle) compared with literature data. **(Right panel)** Percentage variation of the mass fraction variation of heavy isotopes calculated in stellar model based on extrapolation of the new reaction rate of $^{13}C(\alpha,n)^{16}O$ compared with earlier ones.

Based on the calculated reaction rate from the theoretical extrapolation of the measured cross-section data, the astrophysical impact has been also estimated based on different scenarios of reaction rate at stellar temperature using the so-called FuNS evolution code. The results are shown in right panel of Figure 2. 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. These results are summarized in **G. F. Ciani, L. Csedreki et al. 2021** [**3**].

The unprecedented results obtained by the LUNA collaboration have been confirmed by another measurement performed at China Jinping Underground Laboratory by the JUNA collaboration G. Bao et al. Phys. Rev. Letters 129, 132701 (2022). Even if the community recognized the importance of this results, there is still a lot to do to improve the knowledge of s-process. Future prospect is to perform measurement in a wide energy range with angular distribution measurement completed with multi-channel R-matrix calculation considering the other reaction channels of $^{13}C+\alpha$. An overview and summary of earlier and recent experimental studies in a view of future prospect for higher energy measurements are in preparation **L. Csedreki et al. [4].**

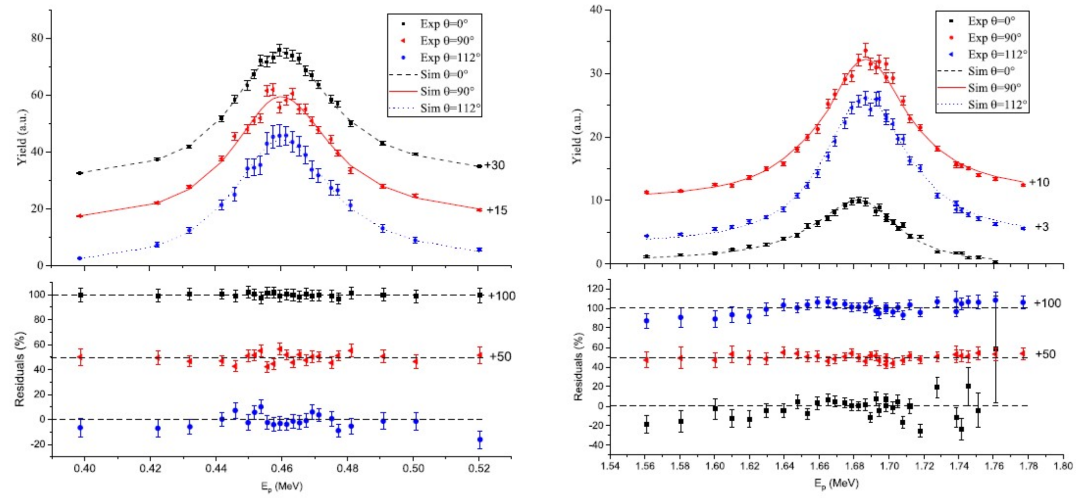
In this part of the project, I was directly responsible for the target production and neutron detection efficiency measurements. I was partially responsible for the data taking at the LNGS laboratory and the analysis of the experimental data. My main contribution for this experiment is shown by my first, corresponding and highlighted position in the author list in the publications.

b. The $^{12,13}C(p,\gamma)^{13,14}N$ reactions

As it was emphasized in Section 1., the cross section of $^{12,13}C(p,\gamma)^{13,14}N$ reactions have to be extrapolated in the $E_{c.m.}$=20-70 keV energy region to properly handle stellar models. Thus, the reaction parameters, such as the reaction cross section, angular distribution and nuclear structure information, such as resonance energies and width need to be precisely known in a wide energy region.

Even if the original project plan focus on the study of the $^{13}C(\alpha,n)^{16}O$ reaction and included supplementary study of neutron production reactions, the acquired experience on the target production and characterisation of evaporated carbon targets and the availability of the experimental apparatus provide the platform for the compact study of $^{12,13}C(p,\gamma)^{13,14}N$ reactions. This included different campaign performed at the Tandetron laboratory of ATOMKI, in the LUNA400 accelerator of LNGS and the Felsenkeller accelerator facility of HZDR.

The study of resonance parameters and cross-section measurement were performed in E_p=300-1900 keV region at the ATOMKI Tandetron accelerators based on in-situ gamma-spectroscopy and activation techniques based on HPGe detectors. The activation method provides the total cross section and has uncertainties different from those of the in-beam γ -spectroscopy technique, the present results provide a largely independent data set for future low-energy extrapolations and thus for astrophysical reaction rate calculations. Moreover, a dedicated measurement using in-beam γ-spectroscopy was carried out in the vicinity of E_p=460 and 1700 keV to obtain resonance parameters, such as resonance energies and widths. These values with reduced uncertainties provide new input parameters for future compilations of $^{12}C(p,\gamma)^{13}N$ reaction and thus for astrophysics cross-section extrapolations. Experimental data obtained at different detection angle in the vicinity of resonances are shown in Figure 3.



3.Figure Experimental data obtained at different detection angle in the vicinity of $^{12}C(p,\gamma)^{13}N$ resonances around E_p=460 and 1685 keV, respectively.

Result of the study of resonance parameters and the cross-section measurement by activation technique are published in separated papers [**5, 6**].

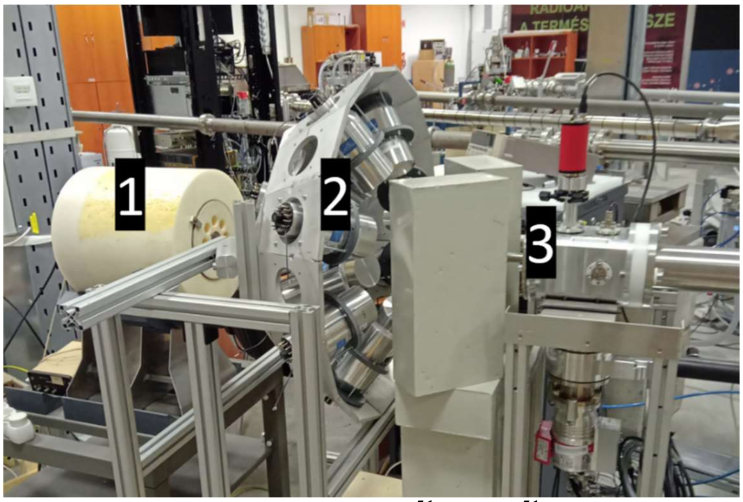
Cross-section measurement of $^{12,13}C(p,\gamma)^{13,14}N$ reaction at low proton energies was performed at the LUNA400 accelerator in the deep underground laboratory of LNGS in $E_{c.m.}$=60-370 keV using in-situ gamma-spectroscopy and activation technique. Our cross sections are the most precise to date with overall systematic uncertainties of 7%–8%. Compared with most of the literature, our results are systematically lower, by 25% for the $^{12}C(p,\gamma)^{13}N$ reaction and by 30% for $^{13}C(p,\gamma)^{14}N$. We provide value of 3.6 ± 0.4 in the 20–140 MK range for the lowest possible $^{12}C/^{13}C$ ratio that can be produced during H burning in giant stars. [**7**]
The extrapolation of the $^{12}C(p,\gamma)^{13}N$ reaction is strongly affected by the resonance near E_p=462 keV. Beside the work done at ATOMKI related to the resonance parameters, the absolute cross section near this resonance was measured at the Felsenkeller shallow underground laboratory in Dresden based on 7-HPGe crystals cluster detector. The obtained S(E)-factor is agreed with LUNA400 result. [**8**]

My contribution for this work included all part of the experiment such as the target production, preparation of the experiments, data taking and data analysis and publication, too. This is shown by my position in the authors list of the different publications.

Summaries of the above-described reactions is also presented in **Ref. [9]**

c. The $^{51}V(p,n)^{51}Cr$ reaction

A significant source of uncertainty of reaction cross-section is assigned by the detection efficiency. In the case of neutron detection, the energy of the available monoenergetic neutron sources is limited and thus complex simulation of the setup and the use of radioactive sources are needed. As a part of the original project plan, the study of the $^{51}V(p,n)^{51}Cr$ reaction and the measurement of its cross section in the $E_{p,lab}$=1600-4000 keV energy range is in preparation at the 2MV Tandetron accelerator facility of ATOMKI using Gamma-ray spectroscopy and activation analysis methods. The test of a $LaBr_3$ detector-based array has already been done involved the measurement of detection efficiency and energy resolution of the setup. The photo of the experimental setup is shown in Figure 4.



1. Figure The experimental setup for the study of $^{51}V(p,n)^{51}Cr$ reaction. Numbers indicate the different part of the setup as a long-counter (*1*) for in-situ neutron detection, LaBr3 scintillation detector array (*2*) for coincidence measurement of prompt gammas and the target chamber (*3*).

The measurement of the $^{51}V(p,n)^{51}Cr$ reaction cross section is planned to be start at the beginning of 2024.

4. Conclusion

The main goals of my PD129060 project were to measure reaction cross-sections of proton and alpha induced reaction on carbon isotopes.

The $^{13}C(\alpha,n)^{16}O$ reaction close its astrophysical s-process Gamow-window was measured as a first time. To perform it, high quality solid states targets were prepared and quantitatively analysed at ATOMKI. High efficiency neutron detection setup was developed for the experiment and it was tested at the ATOMKI infrastructure. The low energy cross-section measurement was performed at the deep underground LUNA400 accelerator. Thus, a better understanding of s-process site in TP-AGB stars became available. The technical details and results were published in three separated papers in peer-reviewed, international journals. An overview of the $^{13}C(\alpha,n)^{16}O$ reaction to focus on future prospects are in preparation.

Another achievement of this project connected to the complex study of the $^{12,13}C(p,\gamma)^{13,14}N$ reactions. Based on ATOMKI measurements the cross-section of the $^{12}C(p,\gamma)^{13}N$ reaction with more precise resonance parameters become available. Due to the low-energy measurement of the $^{12,13}C(p,\gamma)^{13,14}N$ reaction at the LNGS and Felsenkeller underground laboratories, the extrapolation of their S(E)-factors are improved and it allows a better constrain of $^{12}C/^{13}C$ ratio in giant stars.

Another scope the project was the study of proton induced neutron emission reaction. This work is in progress included the test of the gamma detection apparatus and data taking for the study of $^{51}V(p,\gamma)^{51}Cr$ reaction, which as a widely used monoenergetic neutron source has important role in neutron detection efficiency measurements.

Publication in the framework of the PD129060

[1] G. F. Ciani*, **L. Csedreki*** et al., A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha,n)^{16}O$ cross-section measurements at LUNA, *Eur. Phys. J. A (2020) 56:75*, https://doi.org/10.1140/epja/s10050-020-00077-0

[2] L. Csedreki* et al., Characterization of the LUNA neutron detector array for the measurement of the $^{13}C(\alpha, n)^{16}O$ reaction, *Nuclear Inst. and Methods in Physics Research, A 994 (2021)* 165081

[3] G. F. Ciani, **L. Csedreki** et al., Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the s-Process Gamow Peak, *PHYSICAL REVIEW LETTERS 127, 152701 (2021),* https://doi.org/10.1103/PhysRevLett.127.152701

[4] L. Csedreki* et al., Future directions in $^{13}C(\alpha,n)^{16}O$ direct cross-section measurements for astrophysical interest, in preparation

[5] Gy. Gyürky*, **L. Csedreki**, T. Szücs, G.G. Kiss, Z. Halász, Zs. Fülöp, Cross section measurement of the $^{12}C(p,\gamma)^{13}N$ reaction with activation in a wide energy range, *Eur. Phys. J. A (2023) 59:59*, https://doi.org/10.1140/epja/s10050-023-00974-0

[6] L. Csedreki*, Gy. Gyürky, T.Szücs, Precise resonance parameter measurement in the 12C(p,γ)13N astrophysically important reaction, *Nuclear Physics A 1037 (2023) 122705,* https://doi.org/10.1016/j.nuclphysa.2023.122705

[7] J. Skowronski, E. Masha, D. Piatti, M. Aliotta, H. Babu, D. Bemmerer, A. Boeltzig, R. Depalo, A. Caciolli, F. Cavanna, **L. Csedreki** et al., Improved *S* factor of the $^{12}C(p, \gamma)^{13}N$ reaction at E = 320–620 keV and the 422 keV resonance, *PHYSICAL REVIEW C 107, L062801 (2023),* https://doi.org/10.1103/PhysRevC.107.L062801

[8] J. Skowronski, A. Boeltzig, G. F. Ciani, **L. Csedreki** et al., New proton-capture rates on carbon isotopes and their impact on the astrophysical $^{12}C/^{13}C$ ratio, *PHYSICAL REVIEW LETTERS 131, 162701 (2023).* https://doi.org/10.1103/PhysRevLett.131.162701

[9] A.Chemseddine, F. Barile, A. Boeltzig, C. G. Bruno, F. Cavanna, G. F. Ciani, A. Compagnucci, **L. Csedreki** et al., Underground Measurements of Nuclear Reaction Cross-Sections Relevant to AGB Stars, *UNIVERSE 8: 1 p. 4 (2022)* https://doi.org/10.3390/universe8010004

Oral presentation: **L. Csedreki**, Direct measurement of $^{13}C(\alpha,n)^{16}O$ reaction towards its s-process Gamow peak, Nuclear Physics in Astrophysics X, Sep 4-9, 2022, CERN