PROCEEDINGS OF SCIENCE

Cross section of the ^{13}C(α,n)^{16}O reaction at low energies in the framework of LUNA collaboration

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The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source for the *s-process* in low mass AGB stars. Although several direct measurements have been performed, no dataset reaches the Gamow window (140-250 keV) due to the the exponential drop of the cross section σ(E) with decreasing energy. The reaction rate becomes so low that the strong cosmic background would become predominant.

A recent new measurement was carried out in deep underground laboratories of Laboratori Nazionali del Gran Sasso (LNGS) in the framework of the LUNA experiment.

In order to measure the $^{13}C(\alpha,n)^{16}O$ cross section at low energies, a multiple effort has been performed, namely to suppress the background in the setup, to maximise the detector efficiency and to keep under control the target modification under an intense stable beam provided by the LUNA accelerator (100-200 μA). Thanks to these accuracies, the $^{13}C(\alpha,n)^{16}O$ cross section was measured in the center of mass energy range 230<E_{cm}<305 keV with an overall uncertainty of maximum 20%. This allowed to constrain the reaction rate at T=0.1 GK at 10% uncertainty.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

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PoS(PANIC2021)318

1. Introduction

Nuclear cross sections measurements at the energies of interest for stellar evolution are a crucial input parameter for many fields such as cosmology and astrophysics. Nevertheless, these may be very challenging: at average inner stellar temperatures, of the order of MK, the Coulomb repulsion energy among bare nuclei in stellar plasma is much larger than the kinetic energy of interacting nuclei. Therefore nuclear reactions can only occur via tunneling effect. As a result the nuclear cross sections involved are usually small and difficult to measure in a laboratory where signals may be hampered by the environmental background produced by natural radioactivity and cosmic radiation. One possibility to overcome this problem is to measure the cross section at higher energies and a subsequent extrapolation at low energies using the Astrophysical factor S(E)[1]. A decisive contribution in experimental nuclear astrophysics was introduced by the installation of the Laboratory for Underground Nuclear Astrophysics (LUNA) in Laboratori Nazionali del Gran Sasso (Italy), where a natural shielding of 1400 meters of rocks overlying the laboratory guarantees a six (three) orders of magnitude reduction in cosmic muon (neutron) flux.

The LUNA experiment takes advantage from an accelerator providing very stable beams of proton and alpha particles in the energy range 50 keV to 400 keV with a maximum current on-target up to 500 μA, an energy resolution of 0.1 keV and a long term stability of 5 eV per hour [1]. Beam can be focused either on a solid[2, 3] or on a gas target[4]. For cross section measurements of radiative capture reactions at LUNA, a High Purity Germanium detectors (HPGe) and a high gamma detection efficiency segmented BGO ($Bi_4Ge_3O_{12}$) 4π calorimeter are currently used[5]. A lead shielding is designed to optimize the reduction of the environmental background.
In addition, an array of silicon detectors for charged particles detection has been developed by the collaboration[6]. Recently, the LUNA collaboration planned a measurement devoted to neutron detection: the measurement of the $^{13}C(\alpha,n)^{16}O$ cross section.
The aim of this work to describe this measurement: in Section 2 we illustrate the astrophysical motivation and the state of the art of the measurement; Section 3 describes the experimental techniques used are described and the final results are discussed in Section 4.

2. Astrophysical motivations and state of the art

It is well established that the $^{13}C(\alpha,n)^{16}O$ reaction (Q=2.215 MeV) is the major neutron source feeding the *s*-process in low mass ($1-3M_\odot$) Asymptotic Giant Branch (AGB) stars[7], whose temperature of interest is about $1-2\cdot 10^8$ K. This corresponds to a Gamow window between 140[2] and 250 keV, well below the Coulomb potential energy of the reaction.

In the last 25 years, several direct measurements of this reaction cross section have been performed [8–10]. The lowest energy point is for E=265 keV measured by Drotleff et al. [9] with a 60% uncertainty. From the literature one can check that statistical error is due to the low signal to noise ratio at low energy and a strong source of systematical uncertainty comes from the difficulty to keep under control target degradation.

[1]The S(E) factor is connected to the cross section by the relation S(E)=σ(E)E$e^{2\pi\eta}$, where η is the Sommerfeld parameter including the Coulombian effect of the interaction

[2]all the energies are in center of mass system, unless specified

In addition, the presence of a near threshold resonance at $E_R = -3 \pm 8$ keV , corresponding to E_x = 6.356 MeV state in ^{17}O influences the cross section in the Gamow Window, makes extrapolations from higher energies complicated.

The S(E) factor extrapolation uncertainty in the Gamow peak is at least of 20%. A recent work by deBoer et al.[11] states that one of the main source of uncertainty for R Matrix extrapolations is due to normalisation uncertainty of the $^{13}C(\alpha,n)^{16}O$ data, direclty connected to systematic uncertainties on different datasets.

In this scenario the new LUNA measurement, whose goal is to reach the Gamow window with a direct measurement with an overall 20% uncertainty at maximum, finds a perfect collocation that allows to constrain the reaction rate for a better development of stellar evolution.

3. The experimental setup

For the first time, the LUNA collaboration designed and installed a neutron detector at the end of the solid target beamline.

Figure 1a shows the experimental setup used for this measurement: it is based on 18 ^3He counters with low intrinsic background arranged in two rings (6 in the inner ring, 12 in the outer ring) concentric with respect to the target chamber. The counters are embedded in a polyethylene moderator. The whole setup is surrounded by a 2 inches borated polyethylene absorber to further reduce the environmental background [15]. The alpha particle intrinsic background, coming from impurities of uranium and thorium in the counter cases, was reduced using stainless steel counters instead of standard aluminium ones.

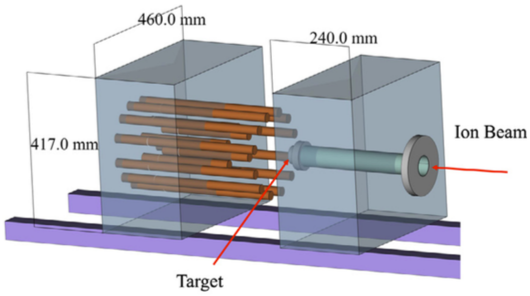
Moreover a pulse shape discrimination analysis of wave functions from the raw preamplifier from detectors allowed the rejection of remaining alpha signals[14] obtaining a final background in the whole setup of about 1 counts/hours. The moderator design allows the opening and the inserting of a High-Purity Germanium (HPGe) detector in close geometry for the target monitoring as explained later.

Figure 1b shows the absolute neutron detection efficiency of the setup. This was evaluated by means of a Geant4 simulation and validated in two different experimental campaigns: at low neutron energies, below 1 MeV, the activation measurement of the $^{51}V(p,n)^{51}Cr$ reaction was performed at the Van Dee Graaff accelerator installed at the Institute for Nuclear Research ATOMKI (Debrecen, Hungary); at high energy a certificated AmBe radioactive source was used, whose average energy is at about 4 MeV. The interpolation of experimental data constrained the efficiency in the region of interest, at E_n=2.5 MeV to a value of (38±3)% [15].

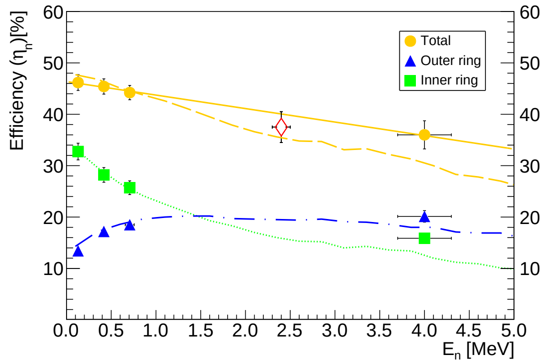
^{13}C targets used during the measurement at LUNA have been produced evaporating ^{13}C isotopically enriched at 99% on tantalum backings.

To check target stochiometry, depth profile and uniformity immediately after the evaporation, an extensive target characterization was performed by means of Nuclear Resonant Reaction Analysis (NRRA) of the $^{13}C(p,\gamma)^{14}N$ reaction at 1.75 MeV at the Tandetron accelerator installed at ATOMKI[12].

The monitoring of these quantities mentioned is crucial also during the cross section measurement performed at LUNA, where the NRRA technique is not applicable, due to the lack of resonances in



(a) Drawing of the neutron detector array used for the LUNA measurement[15].



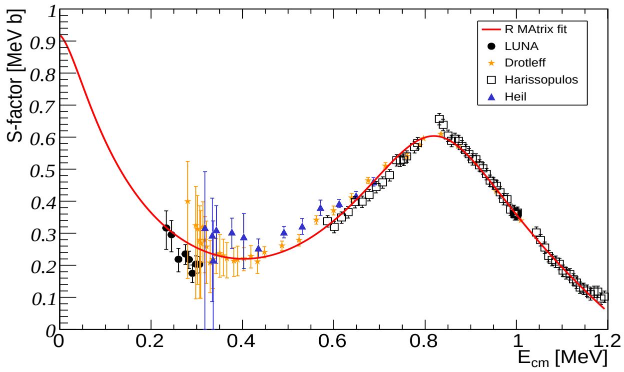
(b) Experimental (filled symbols) and simulated (dashed line) efficiency curves[15]. Efficiencies related to the inner (squares and dotted lines) and outer (triangles and dash-dotted lines) ring of the setups are also shown, respectively. The linear fit of the experimental data (solid lines) allows to interpolate the proposed efficiency value in the experimental region of interest (E_n=2.4 MeV) (empty diamond).

the available energy range. For this reason, a new method of analysis was developed[13].
Data taking at LUNA consisted in long α-beam runs with accumulated charges of $\approx$ 1 C per run, interspersed by short proton-beam runs at E_p= 310 keV with moderator opened and HPGe detector in close geometry, with typical accumulated charges of 0.2 C at most. During the last mentioned proton runs, the target degradation can be checked observing the direct capture de-excitation to the ground state peak of $^{13}C(p,\gamma)^{14}N$ reaction with the HPGe detector.

4. Results and future outlook

Thanks to the impressive background suppression and the novel approach to monitor target degradation, it was possible to measure cross section of the $^{13}C(\alpha,n)^{16}O$ reaction in an energy range between 400 keV down to 305 keV in laboratory system energy, with an unprecedented uncertainty lower than 20% in the entire dataset[17]. Results are shown in Figure 2. The new LUNA data were used together with data by Heil, Drotleff and Harissopoulos for an R Matrix extrapolation using the code Azure2. Finally, the astrophysical reaction rate R=$N_A < \sigma v >$ as a function of stellar temperature was calculated by integration of the R-matrix cross section. For stars of nearly solar composition, we find sizeable variations of some isotopes, 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. With the installation of the LUNA MV facility, with a terminal of 3.5 MV, the LUNA collaboration plans to extend the $^{13}C(\alpha,n)^{16}O$ measurement at higher energies covering the energy range up to 1 MeV. This will give the unique possibility of providing a complete dataset over a wide energy range with well known uncertainties avoiding normalizations[16].

Figure 2: (Colour online) R matrix extrapolation (red curve) of the astrophysical S(E) factor of ^{13}C(α,n)^{16}O calculated using the new LUNA dataset together with the Heil, Drotleff and Harissopulos data. Figure adapted by [17].



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