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s-process Nuclear Reaction Rates

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Abstract. In stars the ^{13}C$(\alpha,\mathrm{n})^{16}$O and ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg reactions are the two main sources of neutrons for the so-called slow neutron capture process (s-process), which is one of the main mechanisms for the stellar synthesis of heavy elements. About ^{13}C$(\alpha,\mathrm{n})^{16}$O, in despite of many efforts in measuring its cross section at the lower energies, only high uncertainty data above the s-process Gamow window (150 keV < E_{cm} < 230 keV) were available, due mostly to the difficulties on suppress the natural background. Indeed, only recently the LUNA collaboration performed high precision underground measurements of the reaction cross section inside the Gamow window, improving the accuracy of its extrapolation at the lower energies. Again due to natural background, only upper limits for the ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg reaction cross section are currently known in the s-process Gamow window (450 keV < E_{cm} < 750 keV). For this, the ERC founded project SHADES (Unina/INFN) aims to perform high precision and high sensitivity measurements of the ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg reaction cross section down to the neutron threshold. A sensitivity improvement of at least two orders of magnitude over the state of the art is expected thanks to the low natural background environment of the INFN-LNGS laboratory in Italy, the high beam current of the new LUNAMV accelerator and the Beam Induced Background events suppression performed by SHADES hybrid detectors array. In this paper I will present the LUNA efforts to estimate nuclear reaction rates for ^{13}C$(\alpha,\mathrm{n})^{16}$O, with a focus on the R-Matrix analysis performed with the code AZURE2 to extrapolate nuclear reaction rates at stellar energies and the estimate of their uncertainty through Monte Carlo methods. I will also present an overview of the SHADES project to measure ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg in the Gamow window and the first results on the setup commissioning.

1 Introduction

Most of the heavy elements in the Universe are produced in low-mass Asymptotic Giant Branch (AGB) stars [1] where ^{13}C$(\alpha,\mathrm{n})^{16}$O burns the ^{13}C-pocket formed in the He layer [2, 3]. The neutron flux associated to this scenario is low and one usually refers to it as s-process (slow neutron capture). It is responsible for the synthesis of elements heavier than A = 90. Although a smaller contribution is also given by the ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg reaction, it is in more massive stars ($M > 8\ M_{\odot}$, solar masses) that this last becomes the main neutron source for the s-process and it is the main contributor for the synthesis of A = 60 ~ 90 elements [4–6].

A precise knowledge of these reactions cross section at stellar energies is required by stellar models to better constraint s-process nucleosynthesis [7, and references therein]. Being at sub-Coulomb energies, direct measurement in the Gamow window are extremely challenging and particular care must be used to suppress environmental background. In the following sections are presented the LUNA collaboration efforts to measure and extrapolate ^{13}C$(\alpha,\mathrm{n})^{16}$O reaction cross section at stellar energies (Sec. 2), as well as the Scintillator-He3 Array for Deep-underground Experiments on the S-process (SHADES) project founded by the European Research Council (ERC), which aims at the measurements of ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg down to neutron threshold energy (Sec. 3).

2 ^{13}C$(\alpha,\mathrm{n})^{16}$O

The s-process energy range (i.e. the Gamow window) for ^{13}C$(\alpha,\mathrm{n})^{16}$O is located at E_0= 150-230 keV[1], far below the coulomb barrier of ~ 3.5 MeV. At these energies, precise measurements of the ^{13}C$(\alpha,\mathrm{n})^{16}$O reaction cross section are very challenging being its value extremely small ($\ll$ pb). Indeed, despite of the many attempts during the years (e.g. [8–12]) measurements could never be performed below 280 keV, with an associate uncertainty of 40% at the lower energies. To improve the status of the art, the LUNA collaboration [13, and references therein] decided to perform a measurement campaign in the low-background environment of the Gran Sasso Laboratories (LNGS) of the Italian Institute of Nuclear Physics (INFN). Reaction neutrons were measured in the LUNA400 facility [14] with 18 ^{3}He counters in 4π configuration placed in a High Density Polyethylene Moderator, which acted both as detector support and as neutron moderator. Due

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[1] Energies are always in the center of mass framework, unless differently stated.

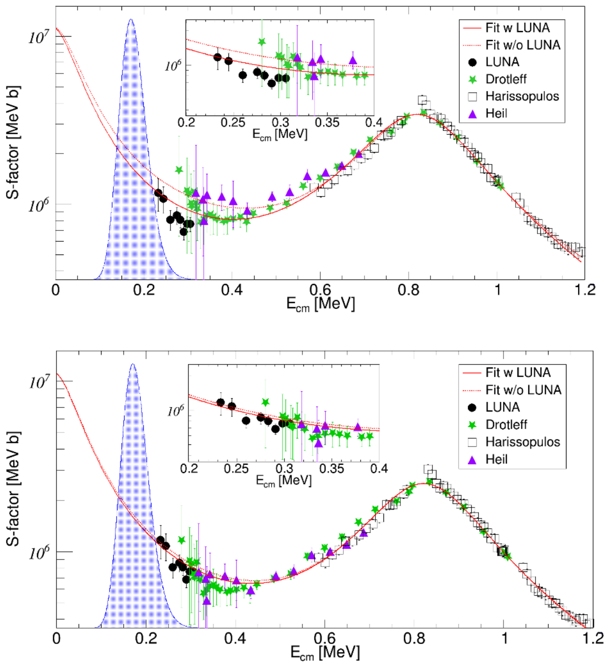

Figure 1. Top: Astrophysical S-factor of $^{13}C(\alpha,n)^{16}O$ using [20] and [21] normalization reference. Red lines are results of two the R-matrix analyses, with and without the LUNA data [19]. The blue curve is the "Gamow peak" at 90 MK. Bottom: Similar chart but with [22] as normalization reference.

to the very low background environment, intrinsic detectors background caused by trace presence of actinides in the aluminum detectors walls had a non negligible contribution, which was reduced by the employ of custom stainless wall detectors. Also the use of the Pulse Shape Discrimination (PSD) technique to identify acquired particles [15–18] allowed for a reduction of the background events to 1.2 ± 0.1 counts/hour which, in addition to the use of 99% enriched ^{13}C targets and the intense α beam current of 150 μA from LUNA400, allowed to perform measurements at beam energies of E_{lab} = 305 - 400 keV with a final statistical uncertainty of 2-18 % [19]. New LUNA data pushed the present low energy limit down to 230 keV entering for the first time the Gamow window.

An R-Matrix extrapolation with the AZURE2 code [23] was then performed including LUNA results to a selection of data from literature [20–22], being representative for the different normalization factors present in data published so far and extending at the lowest energies (see [19] for more details). In Figure 1 are reported the results of the R-Matrix evaluation for the two normalizations. It is worth to notice that the ANC value of the α-bounded $\frac{3}{2}^+$ near threshold state at 7215 keV was fixed with the value proposed [24] and confirmed [12] by indirect measurements. A Monte Carlo analysis sampling resonance parameters in their uncertainty was then performed to extrapolate S-Factor uncertainty. A 13% precision was obtained at the relevant stellar energy for $^{13}C(\alpha,n)^{16}O$, whereas the main contributor is the uncertainty on the ANC value. Considering that lower energies will be hardly accessible for this reaction in the near future [2] an improvement of $^{13}C(\alpha,n)^{16}O$ knowledge could be achieved with a more precise measurement of the 7215 keV state ANC. Furthermore, an investigation at higher energy is required to try solving the normalization discrepancy between data set available in literature.

3 $^{22}Ne(\alpha,n)^{25}Mg$

The s-process Gamow window for $^{22}Ne(\alpha,n)^{25}Mg$ extends down to about 400 keV, whereas the Coulomb barrier is located at a much more high energy of about 5 MeV. This and the neutron background of surface laboratories allowed so far to measure only upper limit for the reaction cross section at the lower relevant energies (see e.g. [20, 26, 27]). To increase our knowledge on s-process and better constraint heavy element abundance in the Universe, the ERC founded SHADES project aims at the measurement of $^{22}Ne(\alpha,n)^{25}Mg$ down to neutron threshold. The measurement will take place at the new LUNAMV facility located at INFN-LNGS where the 1.4 km of overburden rock can already grant a suppression of 2 order of magnitude of the neutron background respect the status of the art. This reduction will be further enhanced by the employ of a new detection array composed by liquid scintillators and neutron proportional counters: neutrons reaching thermal energies inside the scintillators will be measured by the counters. The array will then be able to quantify detected neutron energy to discriminate environmental and beam induced events from reaction ones. Also the use of an enriched ^{22}Ne gas target, recirculated and purified, together with aluminum sealing of the vacuum elements and Tantalum coating of the parts possibly exposed to the beam, will ensure a reduction of the beam induced events, mostly from $^{13}C(\alpha,n)^{16}O$, $^{11}B(\alpha,n)^{13}N$ and $^{11}B(\alpha,n)^{13}N$. Their cross sections are up to 6 order of magnitude more intense respect the one of $^{22}Ne(\alpha,n)^{25}Mg$ and even a small presence of carbon and boron must be avoided.

A cut-view of the SHADES setup is presented in Figure 2. The reaction chamber is surrounded by 18 ^3He counters and 12 EJ-309 scintillators kept in position by a polyethylene holder which serves at the same time as a shield against environmental neutrons. Several gauges and temperature sensors will monitor gas target performances while a Rutherford Back-Scattering Spectroscopy port will allow to measure ion beam current during the reaction yield measurement, for normalization purposes. Collimators at the entrance of the reaction chamber and of the different pumping stages will allow to operate the target in windowless mode.

SHADES detectors are currently under characterization. Preliminary background measurement performed at LNGS showed that the intrinsic background from the α decay of ^{238}U and ^{232}Th (possibly present as trace elements in the detector walls) is clearly identifiable in the scintillators. A forthcoming paper will discuss the PSD analysis

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[2] Recently also the JUNA collaboration measured the same reaction reaching the same low energy limit [25]. Results are in agreement with the one of LUNA.

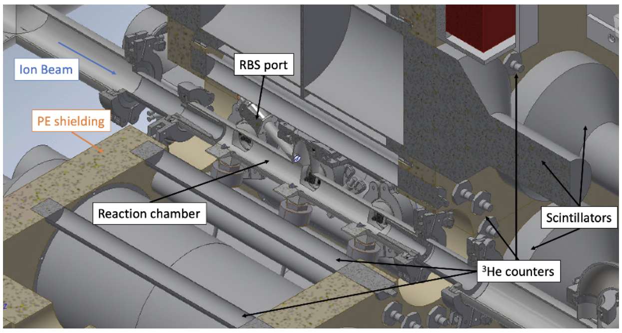

Figure 2. SHADES setup cut-view.

performed to identify particles and the evaluated detector walls activity. Energy calibration measurements were also performed at the Goethe University in Frankfurt through the ^{7}Li(p, n)^{7}Be reaction in the proton energy range E_p of 1.9 - 2.5 MeV, corresponding to neutron energies E_n ranging from 50 to 700 keV. Data analysis is presently ongoing. Similarly, the gas target setup is presently installed at the Tandem accelerator laboratory of the University of Campania "Luigi Vanvitelli" in Caserta (Italy): originally built for radiocarbon measurements [28], this facility was later expanded to perform AMS [29], nuclear astrophysics [30–32] and ion beam analysis with ^{7}Be radioactive beams [33–35]. Ion beam analysis measurements to characterize SHADES ^{22}Ne gas target thickness and density profile are currently ongoing and outputs will be described in a forthcoming paper.

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