NUCLEAR ASTROPHYSICS AT LNL: THE ^{25}Mg(α,n)^{28}Si AND ^{10}B(p,α)^{7}Be CASES*

A. Caciolli

INFN and University of Padua, Padua, Italy

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The Legnaro National Laboratories (LNL) has a wealth of experience in nuclear physics measurements. Recently, a new effort to perform nuclear astrophysics studies has been initiated. This effort started with the collaboration of LNL with the LUNA (Laboratory for Underground Nuclear Astrophysics) Collaboration for the study of targets. After that, in 2012, thanks to a fruitful collaboration between nuclear astrophysicist and nuclear physics groups involved in neutron detection, the study of the ^{25}Mg(α,n)^{28}Si reaction was developed in order to help solving the ^{26}Al puzzle. For the first time, the angular distributions of neutrons emitted by this reaction were studied deeply, founding discrepancies between the previous studies in literature. In 2014, the study of ^{10}B(p,α)^{7}Be was performed in order to give a precise normalisation to the indirect measurements. This study was done by measuring the activated samples and it is still under analysis. A report of the status of the two experiments will be given in this contribution.

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1. Introduction

The goal of nuclear astrophysics is to measure the parameters of nuclear reactions involved in astrophysical scenarios. Those parameters, and in particular the cross sections, are important for stellar models in order to have precise prediction of stellar nucleosynthesis [1]. Nuclear reaction cross sections involving light charged particles are also important in many other fields of research and there has been a great deal of effort to study these reactions for applied physics in recent years [2–4].

The LNL, thanks to their long tradition of nuclear physics studies with different accelerators, offers a perfect environment to perform cross section measurements for nuclear astrophysics and applied physics. In addition,

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the LNL grants the opportunity to treat all fundamental aspects of nuclear physics experiment in the same laboratory, starting from the target production. There is a long tradition of reactive sputtering technique. This method has been used for many years in the LUNA experiments for target production [5–7]. As a matter of fact, targets produced with this technique offer very good resistance against intense beam irradiation and high purity in terms of contaminants introduced in the target during the production process. This is a crucial parameter for nuclear astrophysics measurements where long term irradiations are needed and where the cross section has a high energy dependence.

For the study of the ^{22}Ne(p,γ)^{23}Na reaction, solid targets of ^{22}Ne implanted in Ta backing were produced [8]. Those targets resisted one week of measurements with a beam intensity of 10 μA.

In addition, at the LNL, there is a facility for the production of evaporated targets. This has been used to produce the targets for the two experiments described in the following sections and we are working on the production of Li_2O targets enriched in ^{6}Li in 2016, taking advantage of the LNL chemical laboratory.

At the AN2000 and CN accelerators, facilities for ion beam analysis are also installed. As an example, a study of the Ta_2O_5 targets produced at LUNA was done with this facility reducing drastically the uncertainties due to the target characteristics [9].

The target study and production is not the main core of our measurements at the LNL involving nuclear astrophysics interest. In the following sections, two recent results achieved at the AN2000 and CN accelerators for the study of two important reactions of nuclear astrophysics are summarized.

2. Study of the ^{25}Mg(α,n)^{28}Si reaction

The observation of ^{26}Al gives us the proof of active nucleosynthesis in the Milky Way. However, the identification of the main producers of ^{26}Al is still a matter of debate. Many sites have been proposed, but our poor knowledge of the nuclear processes involved introduces high uncertainties. In particular, the limited accuracy on the ^{25}Mg(α,n)^{28}Si reaction cross section has been identified as the main source of nuclear uncertainty in the production of ^{26}Al in C/Ne explosive burning in massive stars [10], which has been suggested to be the main source of ^{26}Al in the Galaxy. We studied this reaction through neutron spectroscopy at the CN Van de Graaff accelerator of the Legnaro National Laboratories. The ^{26}Al is produced in the Mg–Al cycle by the well-known ^{25}Mg(p,γ)^{26}Al reaction [11, 12]. This reaction has been precisely studied by the LUNA experiment [13] thanks to its underground location [14–16]. While ^{25}Mg(p,γ)^{26}Al produces ^{26}Al, there are other reactions involved in the destruction of this isotope and its seed, ^{25}Mg: ^{26}Al(n,α)^{23}Na, ^{26}Al(n,p)^{26}Mg, and ^{25}Mg(α,n)^{28}Si. Their impact on the ^{26}Al production during C/Ne explosive burning in massive stars has been recently studied and detailed comparisons between data and models have been performed finding strong discrepancies [10]. In particular, Iliadis and co-workers claimed that the nuclear contribution to the ^{26}Al uncertainty is dominated by the uncertainty on the ^{25}Mg(α,n)^{28}Si reaction rate and they underlined the need for new experimental efforts to reduce the errors on the determination of the cross section value [10, 17]. Iliadis and co-workers claimed that the nuclear contribution to the ^{26}Al uncertainty is dominated by the uncertainty on the ^{25}Mg(α,n)^{28}Si reaction rate and they underlined the need of new experimental efforts to reduce the errors on the determination of the cross section value [10]. The relevant energy region for the ^{25}Mg(α,n)^{28}Si in this context is between 1 and 5 MeV. At energies below those relevant for C/Ne explosive burning, the ^{25}Mg(α,n)^{28}Si reaction has also a minor influence on the neutron production for s-processes [18].

At astrophysical energies, the cross section is highly reduced due to the effect of the Coulomb barrier. To extrapolate the data to these energies, it is advantageous to transform the cross section into the astrophysical $S(E)$-factor defined by [1]

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)\,, \tag{1}$$

where $2\pi\eta = 0.989534\ Z_1 Z_2\sqrt{\frac{\mu}{E}}$ is the Sommerfeld parameter, Z_1 and Z_2 are the atomic numbers of the interacting ions. The reduced mass, μ, is expressed in a.m.u. and E is expressed in MeV.

This reaction has been measured by several authors [19–22] before 2014, but still there are high discrepancies between the data in literature as shown in figure 1. A detailed comparison of the existing data can be found in [23], where the details of the experimental apparatus used at the LNL are also described. It is worth to mention that in the energy range above 2.5 MeV, the NACRE Collaboration [24] determines the S-factor by using the Hauser–Fesbach (HF) calculations, while in the energy range below the lowest data reported in the Wieland thesis [21], the S-factor has been considered to be constant. Iliadis and co-workers [10] report a discussion on the data choice by NACRE emphasising the differences between the adopted cross section value and the results published in [20] and [19].

Angular distributions of several branchings of emitted neutrons have been measured at ten different angles by using neutron spectroscopy with the time-of-flight technique. These results are also reported in [23] where all values are tabulated. These experimental results imply the necessity to

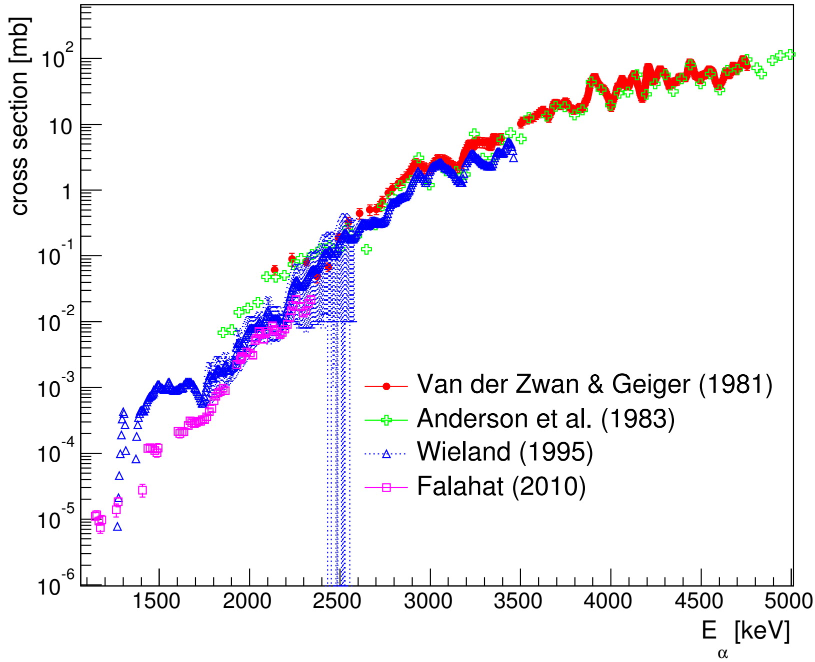

Fig. 1. (Colour on-line) Previous experimental data. The Van Der Zwan and Geiger data are in circles (red), Anderson *et al.* data in open crosses (green), Wielad data are reported in open triangles (blue), and the Falahat data in open squares (pink). It has to be noted that below 1.7 MeV, the Wieland data are only upper limits. NACRE uses only the Wieland data and perform HF calculation at energies above 2.5 MeV.

continue this effort in order to obtain a more reliable and precise cross section for the ^{25}Mg(α,n)^{28}Si reaction. This goal leads to a better understanding of the mechanisms of ^{26}Al production in our Galaxy.

3. Study of the ^{10}B(p,α)^{7}Be reaction

Among the light elements, boron is largely used in many industrial applications and technological solutions, such as semiconductor doping or neutron absorption. Natural boron is composed of two stable isotopes: ^{10}B (19.9%) and ^{11}B (80.1%). Thus, it is important to have precise knowledge of nuclear mechanisms involved with both isotopes. As for example, in new concept fusion reactors [25, 26], the (p,α) reaction on ^{10}B produces ^{7}Be. The production of radioactive ^{7}Be could pose serious radiation-safety problems because of its relatively long half-life, $T_{1/2} = 53.22 \pm 0.06$ d [27]. This calls for precise cross section measurements of the ^{10}B(p,α)^{7}Be reaction in order to understand its impact in future fusion reactor projects.

Boron is also used as a probe of stellar structure for both pre-main-sequence [29] and main-sequence stars [30]. Therefore, boron plays an important role in astrophysics. These elements are destroyed at different depths in stellar interiors and residual atmospheric abundances can be used to constrain mixing phenomena occurring in such stars [30]. Boron burning is triggered at temperatures $T < 5$ MK via the (p,α) process, with a corresponding Gamow energy centred at about 10 keV. At such energies, the cross section, or equivalently its S-factor, is dominated by the s-wave resonance due to the population of the 8.699 MeV ^{11}C resonant level.

The ^{10}B$(p,\alpha)^{7}$Be reaction has been measured by several works. Many of them are reported in the NACRE compilation [24]. A recent work has investigated the S-factor at very low energies by means of the Trojan Horse Method (THM) [31]. A discrepancy of about a factor of 2 is evident between the data in [32] and [33]. In addition, the data in [34] are characterized by high uncertainties. A new direct measurement of the absolute cross section would allow first to have new precise data in a region affected by the previously discussed discrepancy and second to provide to THM measurements a more extended energy region for normalisation purposes.

A new measurement of the ^{10}B$(p,\alpha)^{7}$Be reaction has been done at LNL during December 2014. The cross section has been measured by using the activation technique [1]. Boron samples enriched in ^{10}B up to 93% were irradiated for several hours with a 200–300 nA proton beam. Then, the irradiated samples were inserted in the low-level counting facility of the LNL [35]. The facility is made of two germanium detectors, fully shielded with lead and copper. The ^{7}Be decays were observed by detecting the 478 keV gamma line that is emitted with a branching of 10%. The details of the experimental setup and the analysis are described in [36].

The S-factor of the new data is a factor of 2 higher than [33] and appears in agreement with the trend of data reported by [34]. In addition, the recent data show much lower uncertainties ($< 6\%$) offering a good and precise normalisation for indirect methods.

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