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Target characterizations for a ^{14}N(p,γ)^{15}O cross section measurement

Gy. Gyürky[1,⋆], *A.* Csik[1], *Zs.* Mátyus[1,2], *Zs.* Fülöp[1], *Z.* Halász[1], *G.G.* Kiss[1], *T.* Szücs[1], and *L.* Wagner[3,4]

[1] *Institute for Nuclear Research (Atomki), Debrecen, Hungary*
[2] *University of Debrecen, Hungary*
[3] *Helmholtz-Zentrum Dresden-Rossendorf, Germany*
[4] *Technische Universität Dresden, Germany*

Abstract. The ^{14}N(p,γ)^{15}O reaction controls the rate of CNO cycle hydrogen burning in various astrophysical sites and it is therefore one of the most important reactions in nuclear astrophysics. An experimental program is in progress to measure the ^{14}N(p,γ)^{15}O cross section in a wide energy range using a novel approach. A crucial quantity for the cross section determination is the number of N atoms in the target. In this paper the results of different experiments used for N target characterization are presented.

1 Introduction

Hydrogen burning is inevitably the most important energy source of the universe as this burning makes most of the visible stars shine. The pp-chains and the CNO cycles are the two main processes of hydrogen burning. The first CNO cycle is dominant in main sequence stars more massive than about 1.3 solar masses. The rate of the cycle determines therefore the energy generation and evolution of massive stars. But the small contribution of the CNO cycle to the hydrogen burning of our Sun makes this cycle important also for the better understanding of e.g. the solar composition.

The slowest reaction of the CNO cycle is ^{14}N(p,γ)^{15}O which determines therefore the rate of the whole cycle. The knowledge of the ^{14}N(p,γ)^{15}O reaction rate is thus necessary for the stellar models. The rate is obtained from the reaction cross section which must be known at low, stellar energies. Typically these energies are not accessible experimentally due to the extremely low cross sections. Nuclear theory guided extrapolations are therefore needed which are based on and constrained by higher energy experimental cross sections.

The cross section of ^{14}N(p,γ)^{15}O was measured many times in the past focusing mostly to energies as low as possible (see the review [1] for the list of experiments and ref. [2] for a recent study). Nevertheless, the precision of the ^{14}N(p,γ)^{15}O reaction rate based on the experimental cross sections does not reach the level required for the stellar models. Further experimental study of this reaction is therefore necessary.

The aim of the present work is to measure the ^{14}N(p,γ)^{15}O cross section with a technique never applied for this reaction. The cross section is to be determined with the activation method, i.e. by the measurement of the decay of ^{15}O having roughly 2 minutes half life. An important parameter

⋆ e-mail: gyurky@atomki.mta.hu

for the cross section calculations is the number of N target atoms. In this paper some details of the measurements carried out for the determination of this quantity as well as their results are presented.

2 Target characterizations

Since nitrogen in elemental form is gaseous, for the cross section measurement either a gas target must be used, or a suitable nitrogen compound must be chosen for a solid target experiment. Several previous experiments proved that titanium nitride (TiN) is a well suited solid nitrogen compound for the purposes of cross section measurement. In the present work TiN target were therefore used.

The targets were produced by reactive sputtering of TiN onto thick Ta backings at the Helmholtz-Zentrum Dresden-Rossendorf, Germany using a setup similar to the one described in ref. [3]. In the first phase of the experimental campaign six targets were used with three different nominal thicknesses of 100, 200 and 300 nm. In the next subsections the measurements carried out for the determination of the Ti:N atomic ratio and the actual thicknesses are described.

2.1 Ti:N ratio measurement by X-ray diffraction

Although TiN is known to have well defined Ti:N ratio of 1:1, technological errors during the sputtering process cannot be excluded, so the experimental proof of the ratio is necessary for a reliable determination of the number of N target atoms using the methods shown below. For the Ti:N ratio measurement the X-ray diffraction (XRD) method was used. As the target on a Ta backing is not suitable for a precise XRD analysis, TiN layers onto Si single crystals were also deposited along with the real targets. Owing to the same geometry, the thicknesses of these layers are equal to the layer thicknesses on the Ta backings.

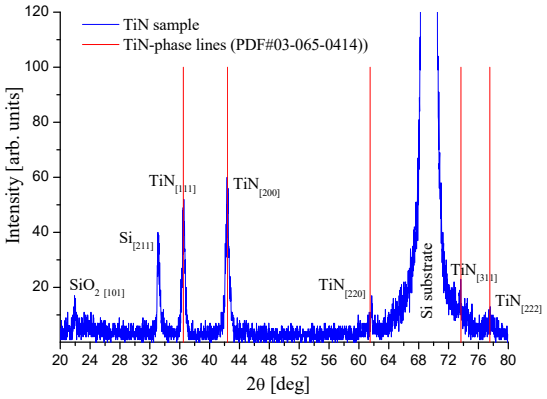

Figure 1. The high angle XRD pattern of the TiN sample. Vertical lines correspond to the TiN phase taken from Powder Diffraction File (PDF) database.

The XRD measurement was carried out by using a diffractometer of Atomki equipped with a Siemens type Cu-anode X-ray tube (operated at 40 kV/30 mA, λ=1.54056 Å) and a horizontal goniometer with graphite monochromator. A high angle symmetric scan was measured in Bragg-Brentano θ-2θ geometry and the standard Powder Diffraction File (PDF) database has been used for identification of diffraction lines. Scan was collected from 20° to 80° 2θ-angle, with a step width of $2\theta = 0.02°$ and a sampling time of 14 sec/step. A piece of the clean Si single crystal was additionally

measured for identification of the substrate lines in diffraction pattern. As it can be seen in Fig. 1 the lines from the standard card of Powder Diffraction File (#03-065-0414) fit well the measured data, which means that the TiN layer has Ti:N ratio of 1:1. All other visible diffraction peaks were identified as Si or SiO lines from substrate.

2.2 Target thickness measurement by SNMS

The mass spectrometry method also was used to determine the composition of the TiN layers. As in the case of the XRD, the layers deposited onto the Si wafers were used for these measurements. Quantitative depth profile analyses of the samples were carried out by Secondary Neutral Mass Spectrometer (SNMS) INA-X type (SPECS GmbH, Berlin) of Atomki [4, 5]. The surface bombardment and post ionization were performed by low pressure Electron Cyclotron Wave Resonance (ECWR) argon plasma. The SNMS was operated in high frequency mode which insured effective charge compensation against surface charge accumulation and thus results in a homogeneous ion bombardment. 350 V sputtering potential at 100 kHz frequency with 80 % duty cycle was applied on a sample surface. The investigated area on the sample surface was confined within a circle of 2 mm diameter by a Ta mask. The lateral homogeneity of ion bombardment was checked by measuring the shape of the sputtered crater with an AMBIOS XP-1 type profilometer. The profilometer was also used to determine the sputtering rate by measuring the crater depth as a function of sputtering time and at the same time to determine the absolute thickness of the samples. Figure 2 shows a typical depth profile of the measured samples. As it can be seen, the top part of the sample contains a low amount of oxygen, nevertheless predominant part of the TiN layer has Ti:N ratio of 1:1.

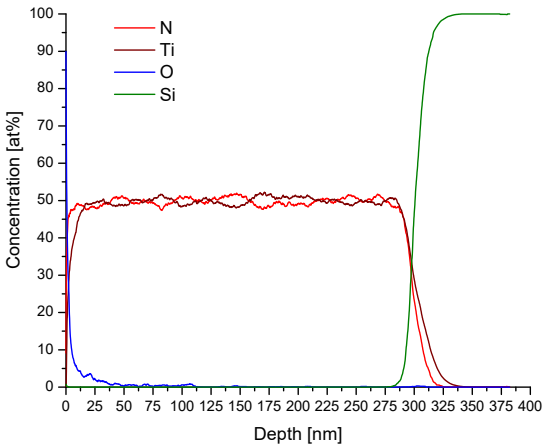

Figure 2. The typical depth profile of the TiN samples measured by Secondary Neutral Mass Spectrometry (SNMS) method.

2.3 Target thickness measurement by nuclear resonance analysis

With a suitable nuclear resonance with small natural width the target thickness can also be measured by Nuclear Resonance Analysis (NRA). As the TiN targets were produced using natural isotopic composition material, the 0.36 % abundance of ^{15}N allows the measurement of the strong resonance in the ^{15}N(p,$\alpha\gamma$)^{12}C reaction at E_p = 897 keV proton energy [6]. The NRA measurements were carried out at the new Tandetron accelerator of Atomki using a setup described in ref. [7]. The resonance profile

of a 300 nm nominal thickness target is shown in Fig. 3. Knowing the Ti:N ratio and the stopping power of protons in Ti and N, the width of the resonance profile provides the target thickness. Taking into account the typically 4 % uncertainty of the stopping power and the 3 % statistical uncertainty of the fit, the target thicknesses could be determined with a precision of 5 % using the NRA method.

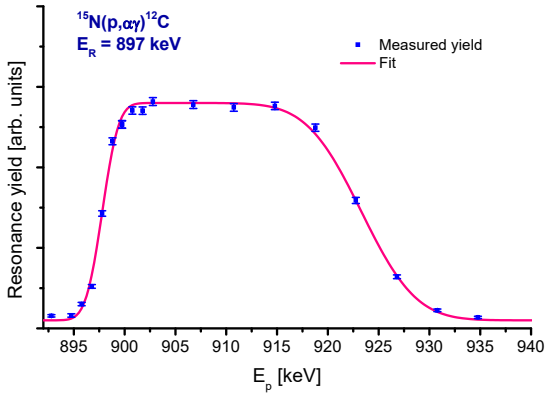

Figure 3. Profile of the $E_p = 897$ keV resonance in $^{15}N(p,\alpha\gamma)^{12}C$ reaction measured on a 300 nm thick TiN target

3 Conclusions

The results of the TiN target thickness measurement carried out with the two methods described above are in perfect agreement and reproduce well the nominal thicknesses from the sputtering process. Just to give an example: the thickness of a nominal 300 nm target was found to be 302 ± 11 nm with the SNMS technique and 295 ± 15 nm with NRA. Based on the XRD and SNMS methods the Ti:N ratio of 1:1 was confirmed with 1.2 % accuracy. The number of N target atoms in the targets used for the $^{14}N(p,\gamma)^{15}O$ cross section measurements is known with an uncertainty of typically 4 %. The cross section measurements are in progress.

Acknowledgments

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