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S-Factor measurement of the ^{12}C(p,γ)^{13}N reaction in inverse kinematics

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Abstract. Hydrogen rich solid targets have been developed and produced to investigate the $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$ reaction in inverse kinematics. The SRIM simulation software has been used to determine the parameters for ion implantation in various materials. Nuclear Resonant Reacton Analysis (NRRA) with the resonant reaction $^{15}\mathrm{N}(\mathrm{p},\alpha\gamma)^{12}\mathrm{C}$ has been carried out to measure the hydrogen content of the produced targets. Measurements of the produced targets at the energy range from $E_{\mathrm{cm}} = 577\,\mathrm{keV}$ down to $E_{\mathrm{cm}} = 191\,\mathrm{keV}$, were performed at the 3-MV Tandetron of Helmholtz-Zentrum Dresden-Rossendorf (HZDR).

1 Introduction

The $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$ reaction is the next-to-slowest reaction and the buildup reaction in the CNO cycle. Thus the reaction is very important for nuclear energy generation in massive stars [1]. In the outer parts of the solar core due to lower temperature (12 MK) [2], the reaction rate is determined by the $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$ reaction. Thus it is of great interest to achieve data of the astrophysical S-factor S(E) for the $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$ reaction at astrophysical interesting energies. Also for modern neutrino physics this reaction is interesting, because it is a source of low-energy solar neutrinos measured in several neutrino experiments like GALLEX, SNO and many more [3–5].

The last study about this astrophysical reaction dates back in the ’70s [6]. Also recent data for the astrophysical S-factor exists only for energies down to $E_{\mathrm{cm}} \geq 300\,\mathrm{keV}$ [7].

2 Experiment

The experiments at the 3-MV Tandetron and the ion implantations at the 40-kV ion implanter were performed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). We used a $^{12}\mathrm{C}^{++}$ beam (2.0 - 7.5 MeV) for the S-factor measurements and a $^{15}\mathrm{N}^{++}$ beam (6.2 - 7.6 MeV) for the target characterisation. The evaporation of the developed targets was also done at HZDR. The prompt γ rays were measured with a HPGe detector with 60 % relative efficiency at an angle of 55° relative to the beam axis.

2.1 Simulations for target production

In order to correctly determine the parameters for the ion implantation, several simulations were done with the

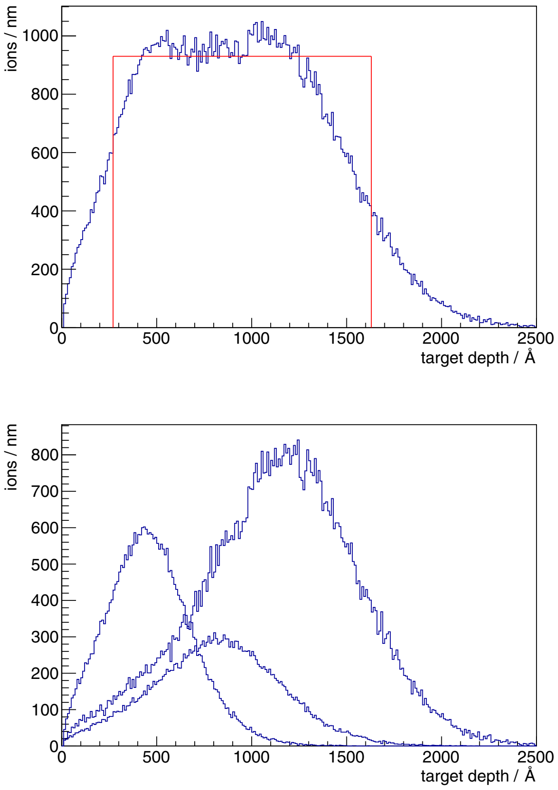

Figure 1. SRIM simulation for zirconium. Bottom panel: Profiles for 3 different ion energies. Top panel: Sum of the 3 implantation profiles. The red line denotes the aimed distribution.

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SRIM [8] simulation software for particle interactions with matter. An energetic width of 0.5 MeV for the ^{12}C ions was aimed for the hydrogen profile. Three different ion energies were necessary to get a nearly box-like profile (Fig.1). From the SRIM simulations two parameters, ion energy and fluence were obtained for the ion implantation (Table1).

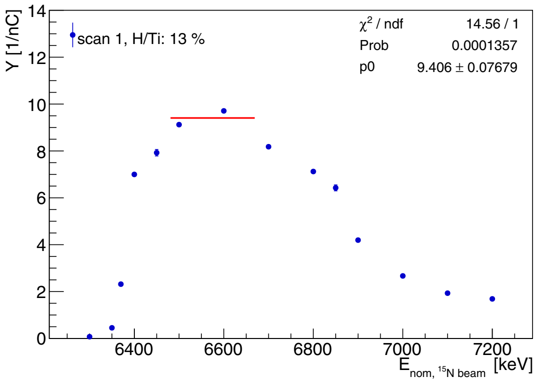

Figure 2. NRRA measurement of a zirconium target with hydrogen content of 13 %, shown in a yield over nominal energy of the ^{15}N^{++} beam

2.2 Target production

The targets consitsts of a tantalum disk of 0.22 mm thickness and 27 mm in diameter. On top of these tantalum backings various metals were evaporated to get 200 nm and 300 nm thick layers. Into this layers hydrogen was implanted to get the mentioned box-like hydrogen profile. Four different materials were chosen for the experiments (Table1).

Table 1. Summary of the parameters used for the target implantation.

Material	Implantation energy [keV]	Weighted fluence in layer [$\times 10^{17}$ atoms/cm^2]
Al	12	6.59
	8	2.64
	5	3.95
Ta	14	4.73
	5	0.75
Zr	15	6.60
	10	2.00
	5	2.60
TiN	11	5.97
	5	3.40

2.3 Hydrogen profile

The hydrogen content of the different material was determined using Nuclear Resonant Reaction Analysis (NRRA). The 4439 keV prompt γ rays of the ^{15}N(p,$\alpha\gamma$)^{12}C reaction at $E_r = 430$ keV and a resonance strength of $\omega\gamma = 21.9$ eV [9] were measured. An average current of 1.5 µA of ^{15}N^{++} beam was used. Close to the target a pressure of (1 - 8)$\times 10^{-7}$ mbar was measured during irradiation. The target scans showed a hydrogen content lower than 1 % in the aluminium and tantalum targets, normalized to the number of atoms in the substrate. Also the target stability of the aluminium was not good enough to perform a measurement with the ^{12}C beam, and the tantalum target was destroyed after short irradiation with ^{12}C. The first stable target was the titanium nitride target with a five times higher hydrogen content than the tantalum target. The TiN and Zr implanted targets are stable enough to use them for the ^{12}C(p,γ)^{13}N S-factor at intermediate energies.

2.4 Outlook

Due to the not yet satisfying hydrogen content we plan to produce implanted targets based on titanium as substrate. Complementary, we try to use hydrogeneation to achieve hydrogen contents exceeding 100 % to measure the ^{12}C(p,γ)^{13}N reaction down to $E_{cm} = 150$ keV.

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