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# S-factor measurement of the $^{12}$C(p,$\gamma$)$^{13}$N reaction in inverse kinematics

**Tobias P. Reinhardt*[a], Klaus Stöckel[ba], Shavkat Akhmadaliev[b], Daniel Bemmerer[b], Stefan Gohl[ba], Stefan Reinicke[ba], Konrad Schmidt[ba], Martin Serfling[ba], Tamás Szücs[b], Marcell P. Takács[ba], Louis Wagner[ba], and Kai Zuber[a]**

[a] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[b] *Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

*E-mail:* tobias.reinhardt@mailbox.tu-dresden.de

The $^{12}$C(p,$\gamma$)$^{13}$N is the second slowest reaction in the CNO cycle. Hence, it affects the reaction rate in the outer parts of the solar core, where due to the lower temperature the CNO cycle has not yet reached its equilibrium. The last comprehensive study of the $^{12}$C(p,$\gamma$)$^{13}$N reaction dates back to the 1970s. Recent data concentrate on $E_{\mathrm{cm}} \geq 300$ keV. The reaction is currently being studied using a $^{12}$C beam at the 3 MV Tandetron at the Helmholtz-Zentrum Dresden-Rossendorf, hydrogen implanted targets and a lead shielded 60 % HPGe detector at an angle of 55° with respect to the beam axis. Hydrogen depth profiling with a $^{15}$N beam was used for the determination of the target characteristics.

*XIII Nuclei in the Cosmos,*
*7-11 July, 2014*
*Debrecen, Hungary*

*Speaker.

 

PoS(NIC XIII)143

**Table 1:** Characteristics of the targets used. The hydrogen content normalized to the number of atoms in the substrate was determined using the $^{15}$N(p,$\alpha\gamma$)$^{12}$C reaction. The reactive sputtering technique was used for the production of the TiN target.

| Substrate | Evaporated width [nm] | Implantation energy range [keV] | Total fluence [$10^{17}$ atoms/cm$^2$] | [H]/[substrate] |
|---|---|---|---|---|
| TiN | 400 | 5-11 | 9.4 | 4% |
| Zr | 300 | 5-15 | 11.2 | 15% |
| Al | 300 | 5-12 | 13.2 | $< 1\%$ |
| Ta | 300 | 5-14 | 5.5 | $< 1\%$ |

## 1. Motivation

Next to the bottleneck in the carbon-nitrogen-oxygen (CNO) cycle $^{14}$N(p,$\gamma$)$^{15}$O, the $^{12}$C(p,$\gamma$)$^{13}$N reaction exhibits the next-to-slowest reaction rate at the core temperature of the sun. However, outside the core at a temperature of 12 MK, the lifetime of $^{14}$N against destruction by $^{14}$N(p,$\gamma$)$^{15}$O exceeds the age of the sun. Consequently, the CNO cycle has not yet reached its equilibrium leading to a second peak in the $^{13}$N neutrino flux. The radius $R/R_\odot$ of its emergence depends on the $^{12}$C(p,$\gamma$)$^{13}$N reaction rate [1].
Apart from a recent study for $E_{\mathrm{cm}} \geq 300$ keV [2], the last comprehensive measurements of the S-factor at lower energies dates back to the 1970s [3]. In this study, we aim to remeasure the low energy tail of the broad resonance of the S-factor with reduced uncertainties.

## 2. Experiment

The irradiations have been conducted at the 3 MV Tandetron of the Helmholtz-Zentrum Dresden-Rossendorf [4] using $^{12}C^{2+}$ ions with a kinetic energy of $2.5-6.5$ MeV and an intensity of typically 25 $\mu$A. Before entering the target chamber, the beam passes a 30° bending magnet, electrostatic quadrupoles, and horizontal and vertical deflector units. A water-cooled collimator with an opening of 5 mm in diameter limits the beam spot. Further downstream, a 30-mm copper tube serves as secondary electron suppression using a bias voltage of -100 V. This extends to within 2 mm of the target surface. During irradiation a pressure of $(1-4)\times10^{-7}$ mbar was measured near the target. The targets consist of an evaporated layer of metal on a backing of 0.22 mm tantalum with a diameter of 27 mm (Table 1 lists the metals used). In a second step, hydrogen was implanted into the evaporated substrate [5] using doses of $(1.0-6.6)\times10^{17}$ atoms/cm$^2$ in an energy range of $5-15$ keV (Table 1). The tantalum backing was directly cooled using deionized water to ensure constant temperature during irradiation.

In order to measure the prompt $\gamma$ rays a high-purity germanium (HPGe) detector of 60 % relative efficiency was used at 55° with respect to the beam axis. The detector as well as the target chamber were shielded with 12 cm of lead resulting in a suppression factor of 32 compared to the laboratory background measured without shielding at $E_\gamma = 2.3$ MeV. Two different data aquisition (DAQ) chains were used after splitting the signal of the HPGe. The signals in the first DAQ chain are shaped and amplified using an Ortec 671 spectroscopic amplifier and subsequently recorded as

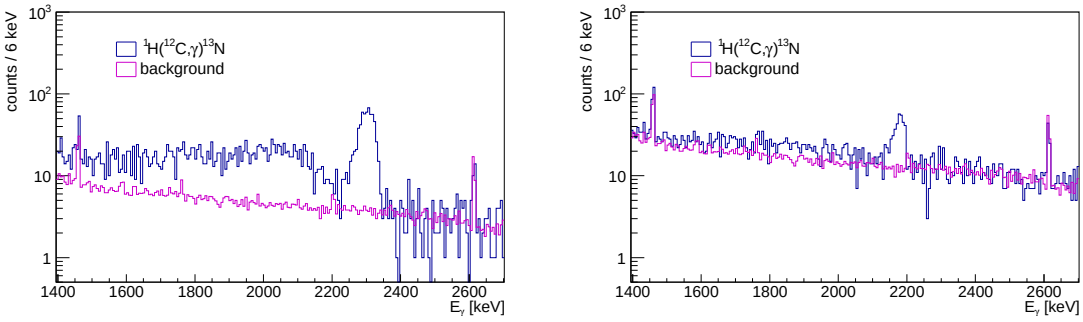


**Figure 1:** In-beam $\gamma$-ray spectrum at $E_{\mathrm{cm}} = 345$ keV (Left panel) and 229 keV (Right panel). The magenta spectrum denotes the beam-off laboratory background. Background lines of $^{40}$K at 1461 keV and $^{208}$Tl at 2615 keV are clearly visible.

histograms in an Ortec 919E analog-to-digital converter (ADC) unit with Gedcke-Hale dead time correction. In the second chain, a CAEN N1728B 100 MHz 14-bit ADC was directly connected to the HPGe preamplifier output. A digital trigger generated inside the unit counted events that fell inside the integration window of a preceding event without using them for event generation. Digitizing, integration, and time-stamping of the pulse shapes were executed by a moving window deconvolution algorithm.

The charge impinging onto the target was measured in $10^{-8}$ C steps using an Ortec 439 digital current integrator and subsequently recorded by the CAEN unit and by a scaler unit.

During irradiation the target stability was monitored using $^{15}N^{2+}$ ions and the 6.4 MeV resonance of the $^{15}$N(p,$\alpha\gamma$)$^{12}$C reaction [6] in inverse kinematics by measuring the 4439 keV $\gamma$ ray. Using this technique, the hydrogen content of the targets was determined. The insufficient stability of the Al target did not allow measurements using the $^{12}$C beam. The tantalum target lost its hydrogen content during the irradiation. In the case of TiN serving as carrier for the hydrogen, an hydrogen content of only 4 % normalized to the number of atoms of the substrate was achieved (Table 1). However, this allowed measurements at intermediate energies. Figure 1 depicts the in-beam $\gamma$-ray spectra at $E_{\mathrm{cm}} = 345$ keV and 229 keV. To the right of the $\gamma$ peaks of the direct proton capture, laboratory background and in-beam spectra are consistent up to 14 MeV thus no beam induced background was observed.

## 3. Summary and outlook

We studied implanted hydrogen targets for the measurement of the S-factor of the $^{12}$C(p,$\gamma$)$^{13}$N reaction in an astrophysical relevant energy range. However, the amount of hydrogen is not yet satisfying for measurements at $E_{\mathrm{cm}} \leq 200$ keV. The implantation of hydrogen in titanium evaporated on tantalum disks is already scheduled. Complementary, we attempt to use hydrogenation of titanium for target production. With titanium hydride ($TiH_2$), a hydrogen content of $>100$ % relative to the substrate would permit measurements of the S-factor down to $E_{\mathrm{cm}} \leq 150$ keV.

## Acknowledgments

This work was supported by BMBF (05P120DNUG) and by the Helmholtz Association through the Nuclear Astrophysics Virtual Institute NAVI, (HGF VH-VI-417).

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