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# Tests of carbon targets for $^{12}$C+$^{12}$C reactions at astrophysical energies

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**Abstract.** As a preliminary step towards measurements of the $^{12}$C +$^{12}$ C reactions at astrophysical energies, we investigate the behaviour of targets under beam bombardment, specifically the quantitative relation between hydrogen and deuterium content of different carbon targets and target temperature. Experiments have taken place at the CIRCE accelerator in Caserta, Italy and preliminary results are presented here.

## 1. Introduction

$^{12}$C + $^{12}$C reactions in stars take place in the carbon burning stage of stellar evolution at a typical temperature of 5x10$^8$ K that corresponds to an energy of $E_0 = 1.5 \pm 0.3$ MeV [1, 2, 3]. At these energies, the carbon burning proceeds through the reactions $^{12}$C($^{12}$C, $\alpha$)$^{20}$Ne and $^{12}$C($^{12}$C, p)$^{23}$Na, known as the $\alpha$ and p channels, respectively.

The way in which carbon is burned depends critically on the mass of the star and it is determined by the rate of the $^{12}$C+$^{12}$C reactions. For this reason, the rate of $^{12}$C+$^{12}$C reactions is one of the key quantities needed to understand the evolution of massive stars (>8M$_\odot$) and the nucleosynthesis of heavy elements [4, 5].

Early investigations of the $^{12}$C + $^{12}$C reactions at low energies go back to 1969. To measure these reactions, different groups have used charged particle detection [6, 7, 8] and gamma spectroscopy techniques [9, 10, 11, 12, 13, 14, 15, 16] to investigate both the $\alpha$ and p channels. To date, the measurement that reached the lowest energy has been the one of Spillane *et al.* with an energy of $E = 2.10$ MeV [16]. The current situation of $^{12}$C +$^{12}$ C reactions measurements is presented in figure 1 extracted from [17]. In this figure, the problems at measuring the $^{12}$C+$^{12}$C reactions are pictured: there are not well understood discrepancies between the different data sets, measurements are still far from the stellar energy range, extrapolations to these energies are very uncertain since the resonant structure of these reactions lead to different theoretical models that predict astrophysical S-factors orders of magnitude different between each other and measurements below $E = 3$ MeV have significant error bars due to contaminants in the

targets [6, 7, 14, 16]. These contaminants are mainly hydrogen and deuterium. When the $^{12}$C beam impinges in the $^{12}$C target, the probability of producing a $^{12}$C $+^{1}$ H reaction is orders of magnitude greater than the probability of having a $^{12}$C $+^{12}$ C reaction because the Coulomb barrier of $^{12}$C $+^{1}$ H is significantly lower than the one for $^{12}$C $+^{12}$ C. Deuterium contributes to the unwanted background by the so called "two step process" [18]. In this process, deuterium is elastically scattered by the $^{12}$C beam at forward angles and then impinges on a $^{12}$C in the target producing a background proton.

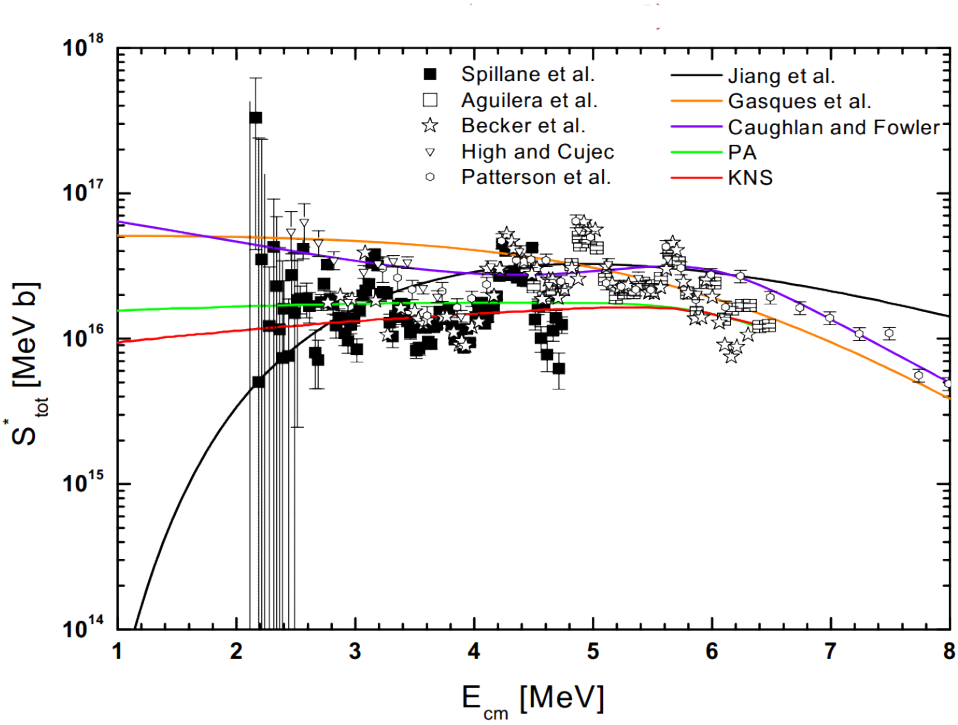


**Figure 1.** Present situation of the $^{12}$C $+^{12}$ C reactions measurements. Astrophysical S*-factor for the $^{12}$C + $^{12}$C reactions as a function of centre of mass energy. Open and filled symbols represent experimental data points (errors are statistical only); curves represent different theoretical models.

Some groups [14, 16, 10] have tried to reduce this target contamination by heating the targets up in different ways, either using resistance heating to increase the temperature to 1800$^{o}$ C of carbon foils ($9 - 88$ $\mu$g/cm$^2$) placed on a tantalum backing [10] or beam heating thick (1 mm) graphite targets at 600$^{o}$ C (for 6-8 hours) [14] and 700$^{o}$ C [16]. In all cases, a reduction in hydrogen content of the targets was found, resulting in cleaner spectra at low energies. Nevertheless, this reduction was never quantified because of time or equipment limitations. Thus, the aim of this work is to quantify the time variation of hydrogen and deuterium content in a target as a function of target temperature using a systematic approach.

## 2. Experimental set up and method

The experimental set up is schematically shown in figure 2. Briefly, it consists in a small chamber housing a water cooled target holder, a detector holder, a detector and a cold finger with an Al foil in front of the detector. The target holder can accommodate two different targets and two collimators of 3 and 6 mm to focus the beam, it is water cooled in order to be able to control the temperature of the target and minimize its degradation. A ($\Delta$E $-$ E$_{\rm rest}$) telescope Si

detector (25$\mu$m and 300$\mu$m, respectively) is placed at 135$^o$ with respect to the beam axis; this type of detector was chosen in order to allow for particle identification. A cold finger to control carbon build-up was used and kept at a potential of -300V to suppress secondary electrons. The cold finger holds a 2$\mu$m Al foil placed in front of the detector to protect it from elastically scattered particles. A quadrupole mass spectrometer (QMS) was used to continuously monitor the composition of the residual gas since the atoms it contains can be easily deposited on the surface of the target increasing its contamination. A FLIR SC325 calibrated thermocamera (accuracy of $\pm$2% at reading) [19] was placed in a chamber's viewport looking through a Ge window. This window is transparent to the wavelengths the thermocamera is sensitive to (7.5$\mu$m-13$\mu$m).

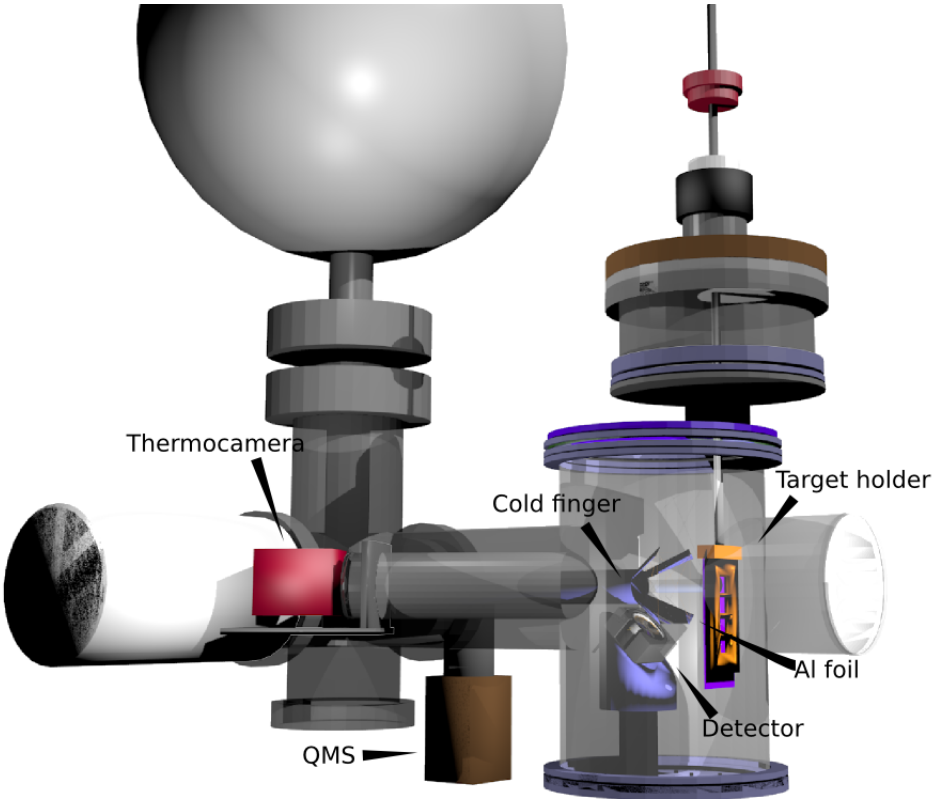


**Figure 2.** Sketch of the experimental set up. Shown are the detector, the target holder, the cold finger, the thermocamera placed outside the chamber in front of a Ge window and the quadrupole mass spectrometer.

Since the purpose of these tests is to quantitatively determine the $^1$H and $^2$H content of our targets as a function of temperature during ion beam bombardment, we employ Nuclear Reaction Analysis (NRA) to quantify the contaminants in the target. We use C, N and O beams coming from the 3 MV pelletron tandem accelerator at CIRCE (Centre for Isotopic Research on the Cultural and Evironmental heritage) laboratory in Caserta, Italy. The thermocamera outside the chamber is used to monitor the target temperature continuously. The thermocamera measurements are attenuated by the Ge window but this attenuation is well known (calibration certificate No. SED04024 by FLIR) and taken into account during the analysis.

For visual purposes, an image taken with the thermocamera facing the interior of the chamber is shown in figure 3. We can clearly identify a part of the target holder and the cold finger as well as the beam on the target in this figure.

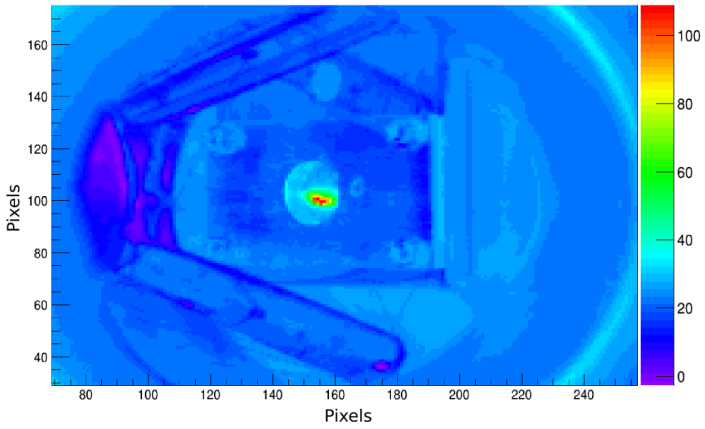


**Figure 3.** Thermocamera picture of target ladder with a beam on the target. The colour bar on the right shows the temperature scale in $^{o}$C.

## 3. Preliminary results

Initial tests were made with a $^{12}C^{+3}$ ion beam of $E = 4$ MeV and an intensity of 7 particle $\mu$A. The beam hit an infinitely thick target (1mm). From the images acquired with the thermocamera it was possible to derive the size of the beam and found it was less than 2.5 mm. The beam constantly heated the target at the beam spot, reaching a temperature of about 500$^{o}$ C in 50 minutes (figure 4).

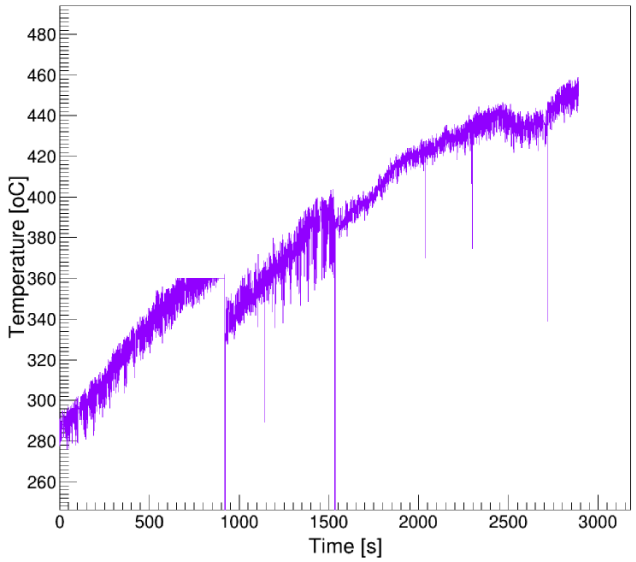


**Figure 4.** Evolution of target temperature (at the beam spot position) as a function of time. Discontinuities in the trend correspond to changes in the temperature range settings of the thermocamera.

A preliminary $\Delta E - E$ matrix is shown in figure 5. The axes correspond to the $\Delta E$ detector energy and the total energy ($\Delta E + E_{rest}$). The most prominent groups in the locus shown correspond to the proton groups from the $^{12}C(^{12}C, p)^{23}Na$ reaction, with $p_0$ corresponding to reactions with $^{23}Na$ left in its ground state and $p_1$ to reactions with $^{23}Na$ left in its first excited state. The total energies of $p_0$ and $p_1$ proton groups are in agreement with the kinematically calculated values. At energies lower than 3 MeV, background events from $^{12}C(d, p)$ reactions due to contaminants in the target were observed as expected given that we did not use highly pure targets for this test. High energy protons can also be seen and presumably correspond to reactions with $^{13}C$ contaminants in the target, although this is still under study.

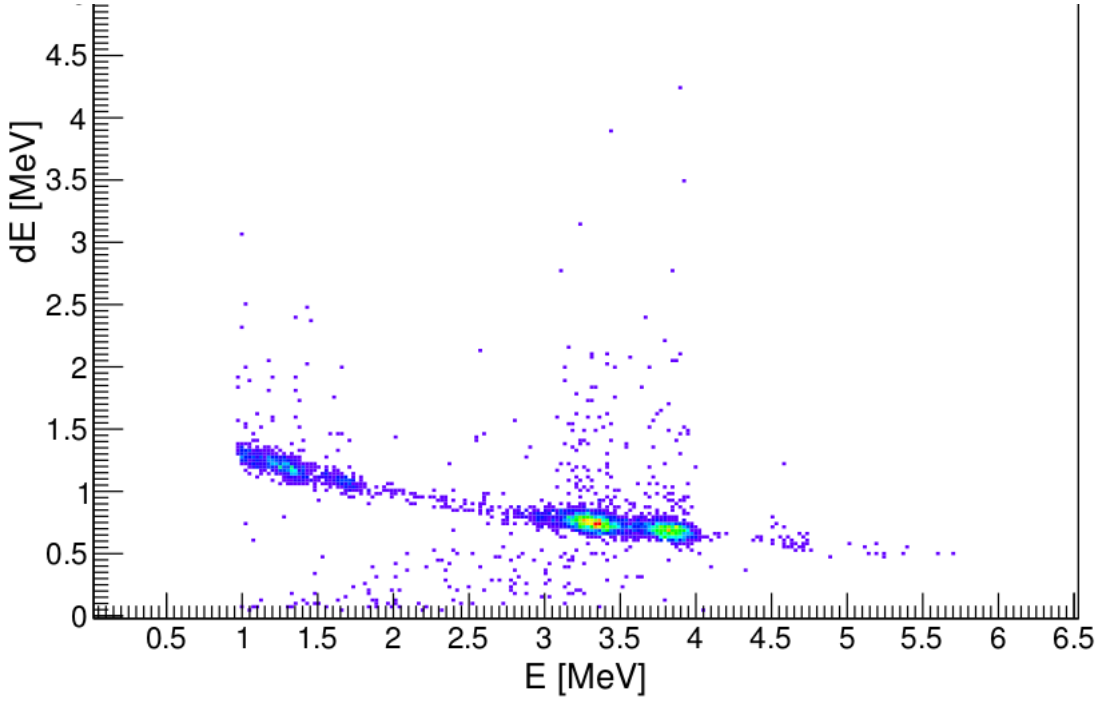


**Figure 5.** $\Delta E - E$ matrix from the telescope detector. The axis correspond to the $\Delta E$ detector energy and the total energy ($\Delta E + E_{rest}$). The most intense groups between 3 and 4 MeV correspond to the $^{12}C(^{12}C, p)^{23}Na$ reaction; protons with lower energies come from deuterium contamination in the target and high energetic protons possibly correspond to $^{13}C$ contaminants in the target.

In order to quantify the H content of the targets we will use targets with known H concentration. The hydrogen content of the target will be continuously monitored during the tests of the target behaviour under beam bombardment. Measurements will be repeated with different beam intensities, thus allowing us to determine the time evolution of the target's H content as a function of target temperature.

## 4. Summary and outlook

We have shown that the designed setup is able to provide a temperature map of the beam impact area on the C target and, concurrently, a measurement of the target's H content. This approach could be extended to other light isotopes, possible sources of beam induced background. Comparative tests of different target materials will be performed to determine the best conditions for the measurements of the $^{12}C + ^{12}C$ fusion reactions. We will also study the composition of

the residual gas with the quadrupole mass spectrometer and put the chamber into a N aquarium to reduce light ions contamination.

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