Direct measurements of the ^{12}C(^{12}C,p)^{23}Na and ^{12}C(^{12}C,α)^{20}Ne reactions at low energies for Nuclear Astrophysics

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Abstract. ^{12}C+^{12}C reactions are crucial in the evolution of massive stars and explosive scenarios. The measurement of these reactions at astrophysical energies is very challenging due to their extremely small cross sections, and the presence of beam induced background originated by the natural ^{1,2}H contaminants in the C targets. In addition, the many discrepancies between different data sets and the complicated resonant structure of the cross sections make the extrapolation to low energies very uncertain. Recently, we performed a direct measurement of the ^{12}C+^{12}C reactions at the CIRCE Laboratory in Italy. Results from a study on target contamination were used, allowing us to measure cross sections at $E_{c.m.}$=2.51 – 4.36 MeV with 10-25 keV energy steps. Two stage ΔE-Erest detectors were used for unambiguous particle identification. Branching ratios of individual particle groups were found to vary significantly with energy and angular distributions were also found to be anisotropic, which could be a potential explanation for the discrepancies observed among different data sets.

1 Introduction

Carbon fusion reactions determine the destiny of massive stars and the properties of a star before a supernova explosion. They are also essential to model X-ray bursts and explosions on the surface of neutron stars [1–10]. With the present knowledge of carbon burning, the Gamow window of these reactions corresponds to $E_{\rm c.m.}$ = 1.5 ± 0.3 MeV [11]. At these energies, the ^{12}C+^{12}C reactions proceed through the ^{23}Na+p and ^{20}Ne+α channels. Carbon-fusion cross sections are extremely small ($\ll 10^{-9}$ b) and thus difficult to measure in the laboratory [12, 13]. In addition, the extrapolation from high energy data to astrophysical

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energies is uncertain by the presence of several resonances and beam induced background due to ^{1,2}H impurities in the target [14–19]. Several attempts have been made over the past five decades to determine the ^{12}C+^{12}C reactions cross-sections [12, 20–34]. However, data still carry large uncertainties and show significant discrepancies between different data sets. Furthermore, no direct measurement has been possible at energies below $E_{c.m.} = 2.14$ MeV and indirect measurements [35] incited an intense debate [36, 37]. For these reasons, further direct experimental investigations are required.

2 Experimental setup

Measurements of the ^{12}C+^{12}C reactions were performed at the 3 MV Pelletron Tandem Accelerator of the CIRCE Laboratory, Department of Mathematics and Physics of the University of Campania "Luigi Vanvitelli" in Caserta, Italy. Thick (1 mm) HOPG targets were mounted on a water-cooled target ladder surrounded by a sphere kept at −300 V for electron suppression, allowing for beam-current reading directly on target. The detection system consisted of four telescope detectors called GASTLY (GAs Silicon Two-Layer sYstem), each comprising an ionisation chamber (IC, ΔE stage) and a large area ($\simeq$ 25 cm^2) silicon strip detector (SSD, E_{rest} stage). Further details on the full detector array and its commissioning are reported in [38]. For the present study, the silicon detector was used as a single pad. Three detectors were mounted on a vertical plane at 121° (D121) and 156° (above and below the beam axis; D156), and one on the horizontal plane at an angle 143° (D143) to the beam axis, as shown in figure 1. See [39] for a full experimental setup description.

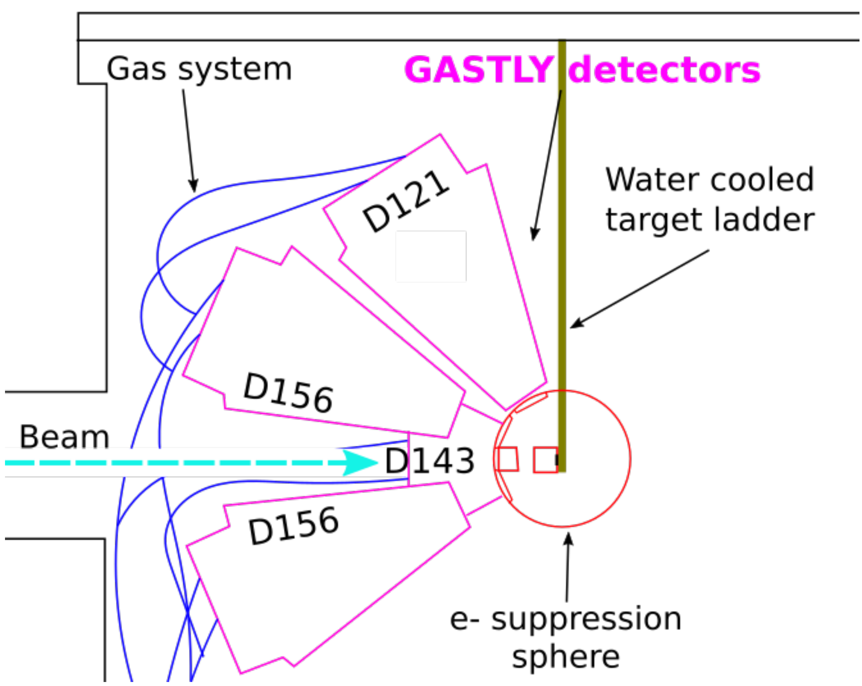

Figure 1. Sketch of the experimental configuration used in this work. Shown are four GASTLY detectors, target ladder, sphere for electron suppression and the beam direction.

Data were taken at energy intervals of 20-50 keV in the laboratory system. Target temperature was constantly monitored with a thermo-camera and maintained to at least 400 °C (using intense beams) to reduce deuterium contamination as a previous study recommends [40]. The scattering chamber was surrounded by an enclosure filled with dry nitrogen.

2.1 Data analysis

For the analysis of each particle channel, background runs of several days were taken, time-normalized and subtracted from the relevant proton and α-particle spectra at each beam energy. Subsequently, proton and α-particle peaks from the $^{12}C+^{12}C$ reactions were identified through kinematic reconstruction and comparing with simulations [41]. As many particle peaks overlap, the number of events within each was extracted using the maximum likelihood method from a combined fit of skewed Gaussian functions. Given that all analysed protons at the energies studied here arrive to the SSD, only its spectra were used in the proton analysis. Some deuterium-induced peaks were still visible (despite its minimization) in the proton spectra. In most cases, it was possible to disentangle this beam-induced contribution from the peaks of interest. Otherwise, the affected proton peaks were discarded from further analysis. Unlike for the proton channel, data analysis for the α-particles channel was performed on reconstructed total energy spectra, (E_{tot} = IC+SSD). Thick-target yields were calculated from the net number of events at each beam energy, then differentiated at two consecutive beam energies to finally extract the differential cross sections. Each cross section was later associated to an effective energy expressed in the centre of mass system and finally converted into $\tilde{S}$-factors. See [39] for a complete description of the data analysis.

3 Results

Differential $\tilde{S}$-factors for individual particle groups were obtained from each detector. In Morales-Gallegos et al. [39] detailed results are reported. Deuterium contamination of the target was identified at all times and thus excluded from the data points. Our data confirm the presence of resonance-like structures across the entire energy region explored in this work, as also reported in previous studies [22, 25, 29, 30, 42]. Given that many working groups assume an isotropic angular distribution and constant branching ratios, we investigated whether such assumptions are correct or not. Even though an angular distribution measurement was not possible due to the use of only three (large) detection angles, our results reveal the presence of anisotropies over all energies. Also branching ratios show significant variations as a function of energy which indicates that they should not be considered constant. Similar results for all proton and α particle groups and angles were obtained.

4 Summary and conclusions

The $^{12}C+^{12}C$ fusion reactions are among the most important in astrophysics as they govern the evolution and fate of massive stars. In this work, we reported on the measurement of the $^{12}C(^{12}C,p)^{23}Ne$ and $^{12}C(^{12}C,\alpha)^{23}Na$ reactions at $E_{\text{c.m.}} = 2.51 - 4.36$ MeV with energy steps < 25 keV in the centre of mass. Background-subtracted proton- and α-particle spectra were fitted with skewed Gaussian functions to obtain the number of events under all particle peaks ($p_0 - p_6$ and $\alpha_0 - \alpha_1$). Cross sections were obtained by differentiating thick-target yields measured at consecutive beam energies and converted into differential $\tilde{S}$-factors. Our results confirm the presence of resonance-like structures as revealed by previous measurements. However, non-constant branching ratios and anisotropic angular distributions were

observed for all particle groups. We note that existing discrepancies among various data sets available in the literature may arise from incorrect assumptions on branching ratios and angular distributions. Improvements to our setup are currently underway: seven GASTLY detectors were produced and mounted at different angles and the SSDs have all their strips fully functioning allowing for an angular distribution measurement.
A thorough study of the intrinsic alpha-emitters contamination of the detectors is being conducted at INFN underground site of the Laboratori Nazionali del Gran Sasso (LNGS) as a joint project between the ERNA and the LUNA collaborations. This in view of a possible use of the GASTLY detectors for the direct measurement of the $^{12}C+^{12}C$ reactions into the Gamow window using the intense carbon beam that will be provided by the upcoming 3.5 MV underground accelerator facility at LNGS (INFN).

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