^{12}C+^{12}C reactions for Nuclear Astrophysics

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Abstract. ^{12}C fusion reactions are among the most important in stellar evolution since they determine the destiny of massive stars. Over the past fifty years, massive efforts have been done to measure these reactions at low energies. However, existing data present several discrepancies between sets and large uncertainties specially at the lowest energies. Factors such as beam/environmental backgrounds, extremely low cross sections and insufficient knowledge of the reaction mechanism contribute to these problems. Recently, the ERNA collaboration measured the ^{12}C+^{12}C reactions at $E_{c.m.}$ = 2.51 - 4.36 MeV with energy steps between 10 and 25 keV in the centre of mass. Representing the smallest energy steps to date. In these measurements, beam induced background was minimised and S-factors for the proton and alpha channels were calculated. Results indicate that a possible explanation for the discrepancies between data sets is the wrongly assumed constant branching ratios and isotropical angular distributions. Given the excellent performance of the detectors for low energy measurements, a collaboration with the LUNA group (LNGS) has started. Background measurements underground are being performed and results indicate it could be possible to measure the ^{12}C+^{12}C reactions directly into the Gamow Window.

1 Introduction

Carbon fusion reactions are among the most important in nuclear astrophysics because of their far-reaching impact on stellar evolution and nucleosynthesis. In particular, the ^{12}C+^{12}C reactions determine the mass threshold for carbon burning to occur, are key for supernova explosions and essential to model X-ray bursts and explosions on the surface of neutron stars.

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Several attempts have been made over the past five decades to determine the $^{12}C+^{12}C$ reactions cross-sections [1–15]. 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 [16] incited an intense debate [17, 18]. 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 (Highly Ordered Pyrolitic Graphite) 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 (25 cm^2) silicon strip detector (SSD, Erest stage). Further details on the full detector array and its commissioning are reported in [19]. For the present study, the silicon detector was used as a single pad. Three detectors were mounted on a vertical plane at 121^o (D121) and 156^o (above and below the beam axis; D156), and one on the horizontal plane at an angle 143^o (D143) to the beam axis, as shown in figure 1. See [20] for a full experimental setup description.

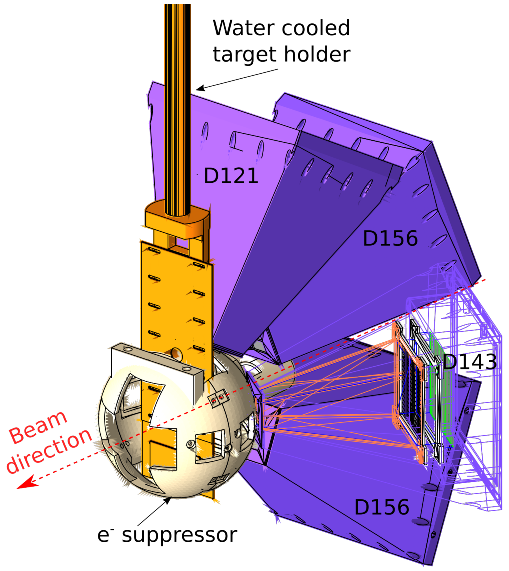

Figure 1. Sketch of the GASTLY detectors arrangement. The four GASTLY detectors are shown along with the target holder and the sphere surrounding it for electron suppression purposes. Detector D143 is shown in wire-frame to reveal its internal components. Figure taken from [20] (published under a Creative Commons Attribution 4.0 International License).

Data were taken at energy intervals of 20-50 keV in the laboratory system. Target temperature was constantly monitored with a thermocamera and maintained to at least 400^{o}C (using intense beams) to reduce deuterium contamination on target by up to 90% its original value, as found in our previous study [21]. With these recommendations and the four GASTLY detectors, the $^{12}C+^{12}C$ reactions were measured using 35-70 mbar of CF_4 in the ionization chambers. Figure 2 shows a typical calibrated ΔE- Erest matrix for detector D121 at a pressure of 35 mbar, obtained with a $^{12}C^{+3}$ beam at E_{lab} = 8.72 MeV on the HOPG target. The two loci correspond to protons and α-particles from the $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$ reactions.

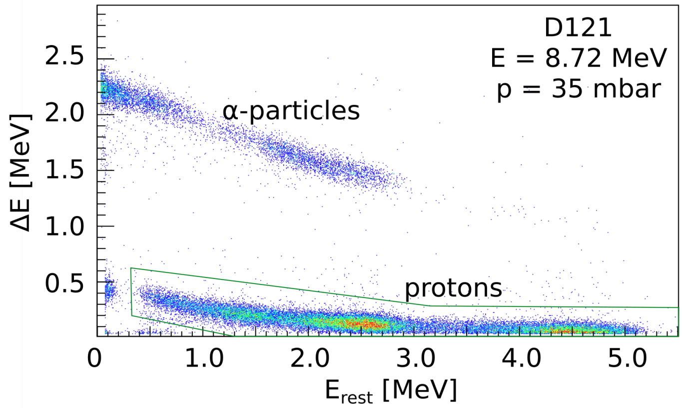

Figure 2. Typical calibrated ΔE - Erest matrix showing the α particles and protons loci. This matrix was obtained using D121 with 35 mbar of CF_4 in the IC and with a E_{lab} = 8.72 MeV $^{12}C^{+3}$ beam impinging on the HOPG target. Figure taken from [20] (published under a Creative Commons Attribution 4.0 International License).

Background runs of several days were taken in the same experimental conditions as the $^{12}C+^{12}C$ measurements and subtracted (after time normalisation) from the corresponding proton and α-particle spectra at each beam energy.

Proton and α-particle peaks from the $^{12}C+^{12}C$ reactions were identified through kinematic reconstruction and comparing with simulations. 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 S -factors. See [20] for a complete description of the data analysis.

3 Results

Differential S -factors for individual proton groups were obtained for each detector as shown in figure 3 for D156. Upper-limits are shown in the form of open symbols. Where data points are missing, this was due to either: (a) difficulties in the fitting procedure due to low statistics and/or poor kinematic discrimination between proton groups (red shaded stripped area); (b) overlap with the deuterium contaminant peak at different beam energies for different proton groups (green shaded area); or (c) low energy protons (high proton-group number) being stopped in the entrance window of the detector.

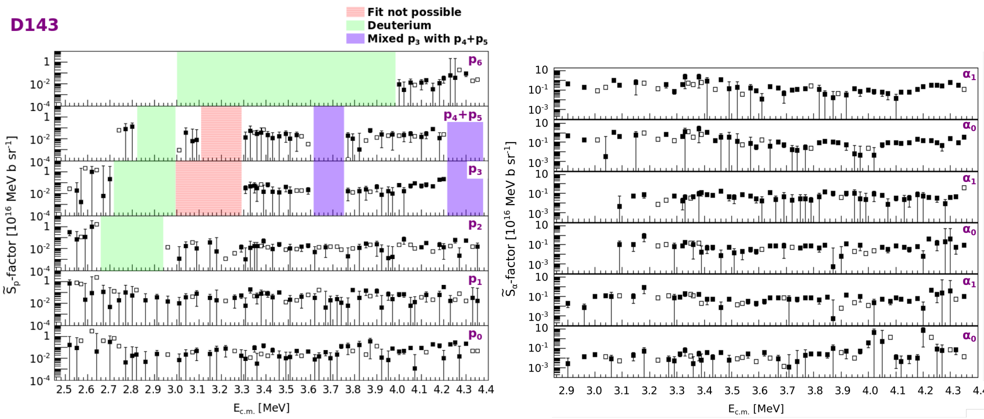

Figure 3. Differential S -factors for individual proton groups obtained with detector D143 (left) and for individual α-particles obtained at all three angles (right). Figures taken from [20] and its supplemental material (published under a Creative Commons Attribution 4.0 International License).

Similar analysis procedures were adopted for the α channel. In this case, however, the ^{12}C+^{1,2}H reactions do not produce α-particles within the region of interest, thus the extraction of cross sections for the ^{12}C(^{12}C,α)^{20}Ne reaction was more straightforward. Differential S - factors are shown for individual detectors and particle group in figure 3.

Our results reveal the presence of resonance-like structures across the entire energy region explored in this work, as also reported in previous studies [7, 10, 13, 14, 22]. On the other hand, non-constant branching ratios and anisotropic angular distributions were observed for all particle groups at most energies, thus preventing the calculation of the total angular-integrated S -factors. See [20] for a complete description and figures.

4 Outlook

The ^{12}C+^{12}C reactions should continue to be investigated. For these reason, a collaboration with the LNGS (National Laboratories of Gran Sasso) of INFN has been established and background measurements have been performed underground using a GASTLY detector (the benefits of moving underground for in-beam measurements of nuclear astrophysical reactions involving charged particles were assessed in [23]). Preliminary results in the conditions of a real experiment indicate a very low intrinsic background affecting only the proton channel. These results already suggest the possibility to measure the ^{12}C+^{12}C reactions underground directly into the Gamow window. Nevertheless, in order to optimise signal to noise ratio, investigations of new materials are ongoing.

Furthermore, an in order to asses the astrophysical impact of new and existing data, an accurate measurement of the ^{12}C+^{12}C reactions angular distributions should be performed. Such measurements have already started at the CIRCE laboratory using the GASTLY detectors and are foreseen down to $E_{c.m.}$=2.0 MeV with fine steps

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