Experimental study of the $^{13}C+^{12}C$ fusion reaction at deep sub-barrier energies

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Abstract. Heavy-ion fusion reactions between light nuclei such as carbon and oxygen isotopes have been studied because of their significance for a wide variety of stellar burning scenarios. One important stellar reaction is $^{12}C+^{12}C$, but it is difficult to measure it in the Gamow window because of very low cross sections and several resonances occurring. Hints can be obtained from the study of $^{13}C+^{12}C$ reaction. We have measured it by an activation method for energies down to E_{cm}=2.5 MeV using ^{13}C beams from the Bucharest 3 MV tandetron and gamma-ray deactivation measurements in our low and ultralow background laboratories, the latter located in a salt mine about 100 km north of Bucharest. Results of the experiments so far are shown and discussed in connection with the possibility to go even further down in energy and with the interpretation of the reaction mechanism at such deep sub-barrier energies.

1. Introduction

We have established a program at IFIN-HH Bucharest-Magurele to test the possibility to make direct measurements for nuclear astrophysics using the new 3 MV tandetron [1] and an ultra-low background laboratory [2] situated in a salt mine at about 2.5 hours drive north of Bucharest. After initial tests of accelerator performances, like beam intensities, stability of beam energies and intensities for long periods of time, and of the logistics involved by irradiations and deactivation measurements at separate locations, we concluded that we could be competitive for reactions induced by alphas and light ions. We report here on extensive tests using a case proposed by our colleagues from IMP Lanzhou.

One of the important questions in nuclear astrophysics is the carbon burning scenario. This process represents the third stage of stellar evolution of massive stars. Until now fusion reaction have only been measured at energies well above the region of astrophysical interest because of the extremely low cross section and signal/background ratio. In stellar environments the reaction rates are estimated by extrapolating measurements done at higher energies, extrapolations that imply a certain degree of uncertainty. For the $^{12}C+^{12}C$ fusion reaction the situation is more complicated because of the resonances occuring below the Coulomb barrier. In contrast with these resonances in the $^{12}C+^{12}C$ fusion reaction, the $^{13}C+^{12}C$ fusion cross reaction behaves more regularly. Therefore direct measurements at the Gamow window energies are essential, but very difficult to carry due to the background from the cosmic rays, terrestrial environment etc. We can make improvements using irradiation de-activation sequencies: we irradiate probes at the new 3 MV tandetron accelerator and move the probes for de-activation measurements in the ultra-low background laboratory in the salt mine. The preliminary results are presented here.

2. ^{13}C+^{12}C Experiment

The resonances from the ^{12}C+^{12}C fusion reaction make it very difficult to measure in the Gamow window, so to be able to test the predictive power of various models and establish a reliable upper limit for the cross section, we studied the ^{13}C+^{12}C fusion cross section at deep sub-barrier energies. The machine has a maximum voltage of 3.2 MV, and it can run as low as 200 kV. During tests we have proven that the accelerator has high and stable beam current in the range of tens of μA for the prolific negative ions (^{12}C, ^{13}C, ^{28}Si, ^{197}Au) and we consider it suitable for α and light ion beams (0.2-1 MeV per nucleon).

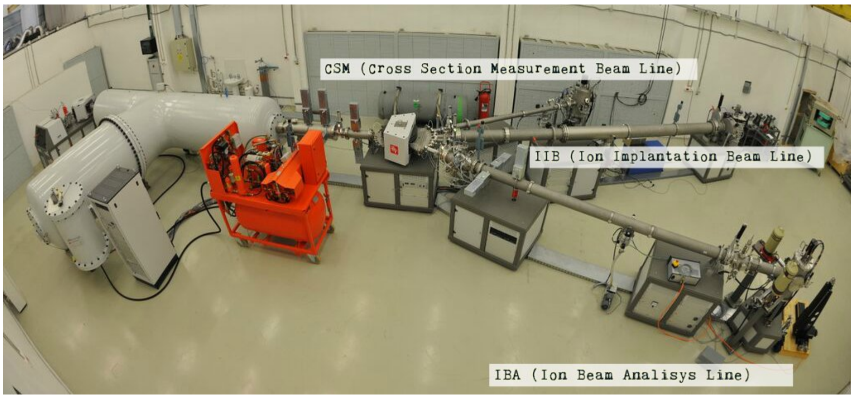

Figure 1. 3 MV Tandetron Accelerator at IFIN-HH [4].

The reaction we chose ^{13}C+^{12}C has the advantage that leads to an activation product with a half-life allowing for the transportation and efficient de-activation measurement. Therefore, our interest was focused on the proton evaporation channel ^{12}C(^{13}C,p)^{24}Na. The experiment had been performed in October 2014. During the experiment the ^{13}C beam in the laboratory energy range of $E_{lab} = 6.8 - 5.2$ MeV ($E_{cm} = 3.2 - 2.5$ MeV), with steps of 0.2 MeV, impinged on 1 mm thick natural carbon targets. Intensities in the range of 2-8 pμA were used in different runs. The irradiation chamber was electrically isolated, acting as a Faraday cup for current integration.

Thick target yield for the ^{12}C(^{13}C,p)^{24}Na fusion reaction was determined through the measurement of the gamma-ray yield following the beta-decay of ^{24}Na ($T_{1/2}$=15 h) at the GammaSpec laboratory at the ground level (in IFIN-HH) and the ultra-low backround laboratory μBq (in the salt mine at Slanic). At the μBq the background decreased almost 4000 times (Fig. 2). In this laboratories the cascading gamma rays (1369 and 2754 keV) were detected with HPGe detectors with 30% relative efficiency (at GammaSpec) and 120% (at μBq in the salt mine) [2]. Their calibration is well known.

The ^{12}C(^{13}C,p)^{24}Na cross sections was calculated from the extracted thick-yield Y(E), using the following equation:

$$\sigma(E) = \frac{1}{N_\nu}\frac{dY(E)}{dE}\frac{dE}{dx}, \quad (1)$$

where N_ν is the number density of target nuclei present in the target and dE/dx is the stopping power.

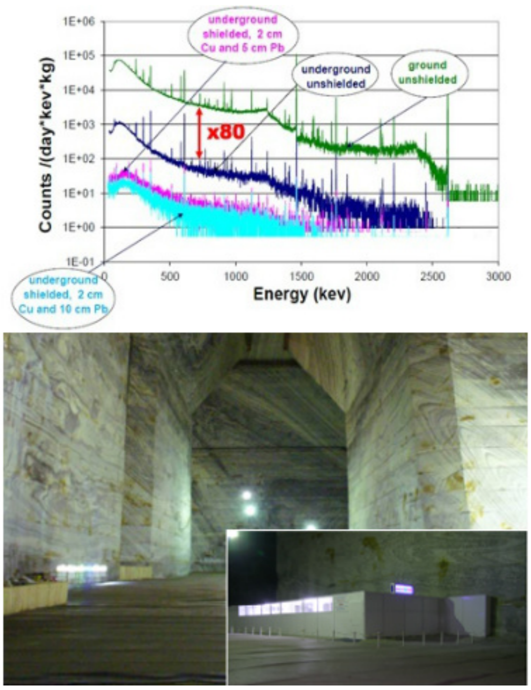

Figure 2. μBq laboratory and background from the salt mine [2].

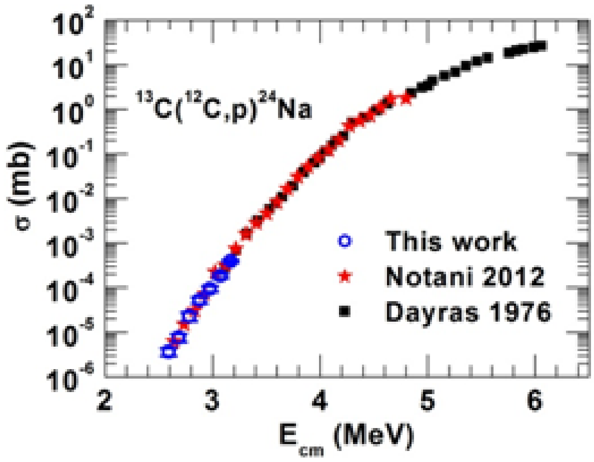

Figure 3. Preliminary cross section of ^{12}C(^{13}C,p)^{24}Na from our experiment and results from the previous experiments.

As you can see (Fig. 3) we went down to the lowest energy ever reached E_{cm}=2.5 MeV and have obtained a good agreement with the past experiments [3-5]. Proton-evaporation cross section were determined and statistical model calculations were used to evaluate the total reaction cross section.

3. Summary

We have made a number of irradiations at the 3 MV tandetron and measured the ^{12}C(^{13}C,p)^{24}Na thick-target yield. The activation measurements were done at the low background laboratory GammaSpec and the ultra-low background laboratory μBq in the Slanic-Prahova salt mine. We went down to the lowest energy ever reached for this reaction (E_{cm}=2.5 MeV), where the cross section was of 4 nb. We have obtained a good agreement with the past experiments and for this year experiment (October 2015) we plan to go to even lower energies. For the ground level measurements (at IFIN-HH) we plan to perform beta-gamma coincidences to further clean the background.

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