# Measurement of the energy-differential cross-section of the $^{12}$C(n,p)$^{12}$B and $^{12}$C(n,d)$^{11}$B reactions at the n_TOF facility at CERN

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**Abstract.** Although the $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ reactions are of interest in several fields of basic and applied Nuclear Physics the present knowledge of these two cross-sections is far from being accurate and reliable, with both evaluations and data showing sizable discrepancies. As part of the challenging n_TOF program on (n,cp) nuclear reactions study, the energy differential cross-sections of the $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ reactions have been measured at CERN from the reaction thresholds up to 30 MeV neutron energy. Both measurements have been recently performed at the long flight-path (185 m) experimental area of the n_TOF facility at CERN using a pure (99.95%) rigid graphite target and two silicon telescopes. In this paper an overview of the experiment is presented together with a few preliminary results.

# 1 Introduction

A precise and accurate knowledge of the cross section of the $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ reactions is important for basic and applied Nuclear Physics. In radioprotection as well as in hadrontherapy, the $^{12}C(n,p)^{12}B$ reaction plays a role in estimating the dose to the tissue, released by the two charged particles produced in the reaction: a proton from the primary reaction and an energetic electron (6.35 MeV average) from the $\beta$-decay of $^{12}B$ [1]. The knowledge of this reaction cross-section is also important for the design of shields and collimators at accelerator facilities, spallation neutron sources and irradiation facilities for fusion materials. Furthermore, it plays a fundamental role in the simulations of the response of diamond detectors to fast neutrons [2]. Reliable cross-section data on these two reactions may also help refine theoretical models of charged particle emission from light nuclei, better characterizing pre-equilibrium effects.

The cross-section of the $^{12}C(n,p)^{12}B$ reaction is highly uncertain, as shown in Fig.1, where experimental data available [2–7] and various evaluated libraries are reported. Large discrepancies, as large as a factor two or more in some case, are present both for the width and the height of the cross section peak, as well as for the position of the reaction threshold. In addition, an integral measurement of this reaction from the threshold energy (∼13.6 MeV) up to 10 GeV has been recently performed at the neutron time-of-flight facility n_TOF at CERN [8] providing an integral value significantly higher than suggested by the available datasets and by most of the evaluated nuclear data libraries [9, 10].

Concerning $^{12}C(n,d)^{11}B$, there are only two data sets in literature. Together with the evaluations based on calculations or indirect measurements, they show the same level of discrepancies as the $^{12}C(n,p)$ reaction [3].

In order to shed some light on this situation and to provide new accurate data, an high resolution energy differential measurement of the two cross-sections has been per-
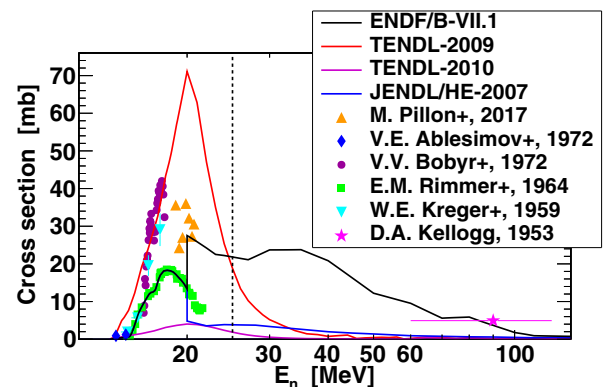


**Figure 1.** Compilation of the available experimental and evaluated data on the $^{12}C(n,p)^{12}B$ reaction cross-section. Huge discrepancies can be observed at the peak of the cross-section.

formed at the n_TOF facility at CERN [11]. The details of the experiment and a few preliminary results will be given in the following sections.

# 2 The experimental setup and the measurement

The measurement of the energy-differential cross section of the $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ reactions has been performed at the first experimental area (EAR1) of the n_TOF facility.

At n_TOF neutrons are produced by spallation induced on a lead target by 20 GeV protons from the Proton Synchrotron accelerator. The well characterized neutron flux approaching EAR1, located at 185 m from the spallation target, features a high instantaneous intensity ($10^5$ n/cm$^2$/pulse), a wide neutron spectrum (0.025 eV - 1 GeV) and a low repetition rate (<0.8 Hz) [12].

The sample used consisted of a 99.95% pure rigid graphite target (C) 0.25 mm thick. This thickness has

been chosen in order to ensure the optimal ratio between reactions yield and self absorption of the outgoing light charged particles emitted. In addition, the C target was tilted by 45° with respect to the direction of the neutron beam in order to increase the reaction yield.

The measurement relied on the detection and identification of the emitted protons and deuterons by means of two silicon telescopes. To this aim, two telescopes were placed at two different angles (backward and forward angles) outside of the neutron beam but close to the C sample, ensuring a large solid angle coverage (∼10°-150°). Each telescope consisted of a thin and a thick silicon strips detector, 20 and 300 $\mu$m thick respectively. Each layer had a surface of 5×5 cm$^2$ divided in 16 strips having 3 mm width each. The assembly of the detectors and the target was hosted in vacuum in a scattering chamber directly integrated in the neutron beam line in order to avoid any background contribution due to the interaction on neutrons with the windows of line elements. A sketch of the setup is represented in Fig.2. More details on the performance of this detection system, already used for other (n,cp) measurements at n_TOF can be found in Ref. [13, 14].
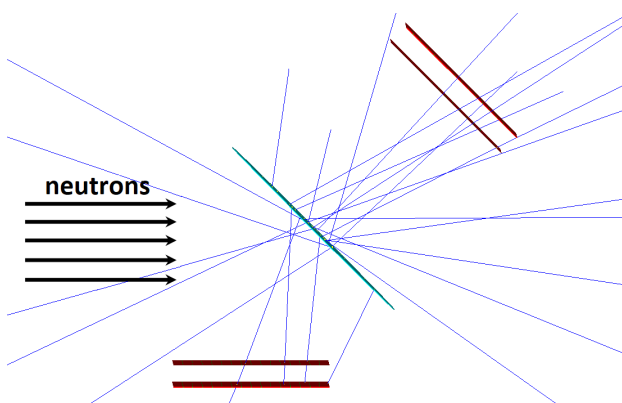


**Figure 2.** Sketch of the setup used in the measurement. The sample was tilted by 45° with respect to the neutron beam direction in order to increase the reaction yield while two silicon telescopes were placed outside of the beam but close to the sample to ensure a large coverage of the solid angle.

The experimental setup was completed by a standard commercial front-end and readout electronics. The preamplifiers consisted of 64 units of CAEN-A1422H-F3 (90 mV/MeV gain) while as amplifiers, a set of 16-channels CAEN-N568B modules were chosen to shape the output signals. The analog signals were then digitized using Acqiris flash ADCs with up to 14 bit resolution and up to 2 GHz sampling rate.

In order to monitor the stability of the neutron beam in view of providing an accurate result for the absolute value of the energy differential cross-sections extracted, a $^6$Li based silicon neutron monitor [15] was installed downstream with respect to the chamber hosting the two telescopes.

## 3 Discussion on the outcome of the experiment and the expected uncertainties

The experimental setup used in the measurement guarantees, together with the identification of the charged particles emitted in the reactions, also the measurement of their angular distributions. In addition, the correlations between neutron time of flight (TOF) and proton/deuteron energy deposition allow to disentangle the contribution of other competing (n,cp) reactions, i.e. the $^{12}$C(n,np) channel opening at ∼20 MeV and becoming rapidly dominant above 25 MeV and setting therefore an upper neutron energy limit for the present experiment.

It is worth noting that the residual nucleus of the reaction under study can be produced in the ground state as well as in the first excited levels. As a consequence, in the case of $^{12}$C(n,p)$^{12}$B reaction for instance, the protons emitted could have energy falling below the experimental threshold applied. In order to correct for these missing levels the total cross section can be extracted using a similar method to the one described in Ref. [16]. Experimental and/or theoretical branching ratios (BR) available can be used to this aim and it should be noted that although the theoretical and experimental branching ratios show some differences the efficiency correction obtained with either the theoretical or the experimental BR differ by less than 10% at all energies. This is the main source of uncertainty in the measurement, dominating by far the total uncertainty budget. We remind that a 10% uncertainty on the cross section for the $^{12}$C(n,p) reaction is clearly adequate to solve discrepancies between previous data and current evaluations.

## 4 Preliminary results

Prior to the measurement with the C sample, a LiF sample 480 $\mu$g/cm$^2$ thick was exposed to the neutron beam, with the aim of using the well known $^6$Li(n,t)$^4$He cross-section to calibrate the setup in terms of energy deposit in the silicons and neutron energy range of reliability of the data collected. It was found that the system could provide data up to at least 60 MeV neutron energy, well above the aforementioned upper energy limit for the physics case under investigation. In addition, data with the bare empty sample frame were collected, showing that essentially no background signals are due to the beam itself.

In Fig. 3 the dE-E matrix for a selected couple of thin-thick strips is reported. The spectrum corresponds to TOF of neutrons in the energy range 1-50 MeV and it shows clearly the expected protons hyperbola in the left part, well separated from the deuterons contribution. On the right part of the plot the alphas contribution is also visible and well separated. Detailed GEANT4 simulations of the experimental setup confirm this interpretation of the data.

In Fig.4 the counts falling in the deuterons region of Fig.3 are distributed as function of neutron energy after performing the TOF to neutron energy conversion. In the same plot also the background contribution evaluated by means of the bare empty sample frame is reported,
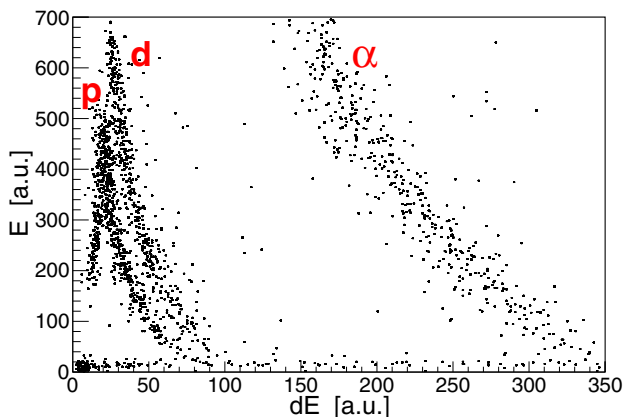
**Figure 3.** dE-E scatter plot corresponding to the C sample exposed to the neutron beam. The three regions from left to right correspond to proton, deuterons and alphas. For the protons the expected punch-through is also visible.

showing the extremely favorable signal-to-background ratio once the (n,d) reaction channel opens. Whereas the spectrum corresponds to a couple of strips covering a small fraction of the solid angle and in the next steps of the data analysis it has to be corrected by the sample mass, the efficiency and the neutron flux, it is strongly related to the $^{12}C(n,d)^{11}B$ cross-section, showing for the first time experimental data at the reaction threshold.
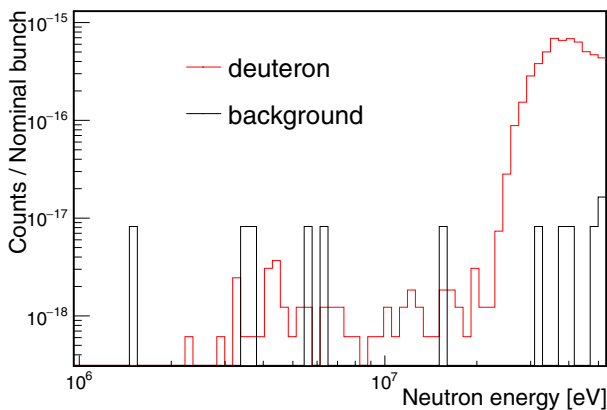


**Figure 4.** Deuterons count-rate (red curve) per neutron bunch as a function of neutron energy for a selected couple of thin-thick strips versus background contribution (black curve) The background was estimated using an empty sample frame.

## 5 Conclusions

The energy differential cross-sections for the reactions $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ have been measured at the n_TOF facility at CERN, with the aim of clarifying the discrepancies in the few scarce datasets already existing in literature. The measurement has been performed by means of two silicon strips telescopes capable of providing also information on the energy differential angular distributions of the two reactions. The expected final uncertainty of the measurement is ~10-15%, mostly depending on the correction for excited states of the residue nuclei.

Thanks to the well-suited features of the n_TOF facility, the preliminary results show the excellent performances of the telescope, in particular in terms of resolving power and wide neutron energy coverage, hinting at the fact that new accurate data on $^{12}C(n,p)^{12}B$ and $^{12}C(n,d)^{11}B$ reaction cross-sections can be provided by this experiment.

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