EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Energy-differential measurement of the ^{12}C(n,p) reaction

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Abstract:
An energy dependent cross section measurement of the ^{12}C$(n,p)^{12}$B reaction is proposed, from the reaction threshold at 14 MeV, up to 25 MeV. A silicon telescope will be used for the detection of protons emitted in the reaction. The correlations between neutron time of flight and proton energy deposition will be used to discriminate between protons from the ^{12}C(n,p) reaction and from the competing (n,cp) reactions. Combined with the previous integral measurement performed at n_TOF, the differential measurement proposed herein will provide accurate new data on this reaction from threshold to 25 MeV. In particular, the new n_TOF data will help to resolve the current, highly uncertain and discrepant experimental data around the reaction threshold. These results could be used to refine models currently used in Monte Carlo simulations.

Requested protons: 2×10^{18} protons on target
Experimental Area: EAR1

1 Motivation

The cross section of the ^{12}C$(n,p)^{12}$B reaction is highly uncertain, as evident from the large discrepancies between the experimental data available in EXFOR [1, 2, 3, 4, 5, 6] and between various evaluated libraries (Fig. 1). An integral measurement of this reaction from the threshold energy (13.6 MeV) up to 10 GeV was recently performed at the n_TOF facility [7, 8], yielding an integral value significantly higher than suggested by the available datasets and by most of the evaluated nuclear data libraries. This level of uncertainty is also directly reflected in the different models currently used in Monte Carlo simulations (in particular in GEANT4), which are unable to consistently predict the measured integral yield of the reaction, while nothing can be said at present about its energy dependence. The three models considered in GEANT4, i.e. Bertini, Binary and INCL++ show a large disagreement between themselves and with the experimental n_TOF value, as clearly illustrated in Fig. 2. A better reproduction of n_TOF integral cross section is obtained with a combination of two different models (denoted as Binary/Bertini in Fig. 2), but even in this case the agreement is not perfect.

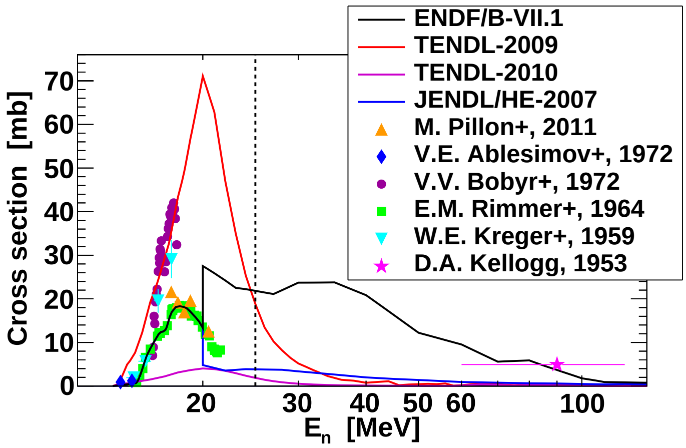

Figure 1: Compilation of the available experimental and evaluated data on the ^{12}C(n,p)^{12}B reaction. A dashed line indicates that the peak of the cross section is well captured below 25 MeV (the expected limit for the proposed measurement).

Previous measurements and theoretical estimations suggest that the cross section peaks around 20 MeV. In fact, it is predicted that the largest contribution to the integral value comes from the energy region between the reaction threshold and 25 MeV. The large differences between the few existing measurements just above the reaction threshold do not allow to draw a conclusion on the width and height of the cross section peak.
An accurate differential measurement covering the peak region would be important for a series of applications of relatively low-energy neutrons and proton beams. 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 [9], since this reaction leads to the release of two charged particles: a proton from the primary reaction and an energetic electron (6.35 MeV average) from the β-decay of ^{12}B. The knowledge of the 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.. Finally, it is crucial for simulations of the

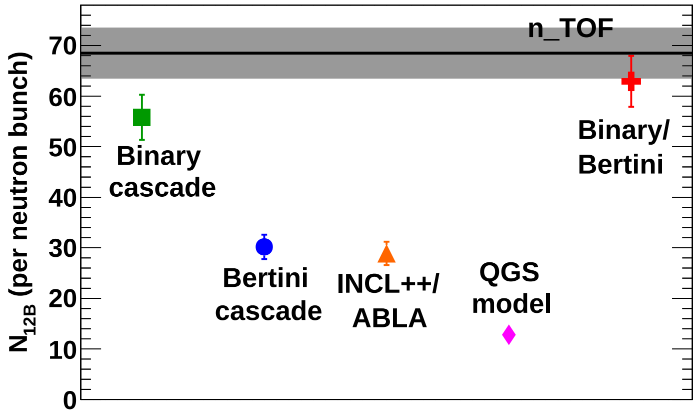

Figure 2: Number of produced ^{12}B nuclei per single neutron pulse of the n_TOF beam, according to the different GEANT4 models, compared to the integral n_TOF result.

response of diamond detectors to fast neutrons, in view of the increasing importance of these detectors in neutron irradiation studies. The energy range around 20 MeV is well within the reach of the n_TOF experiments.
Considering the importance of this reaction for a variety of applications, as well as for the understanding of nuclear structure of light nuclei, we propose to perform the energy differential measurement of the ^{12}C(n,p) reaction in the Experimental Area 1 of the n_TOF facility, from the reaction threshold at 14 MeV, up to 25 MeV, with the aim of reducing the large uncertainty in current evaluated cross section libraries.

2 Experimental details

While the integral measurement of the ^{12}C$(n,p)^{12}$B reaction was performed by detecting the β-rays from the decay of ^{12}B nuclei produced in the reaction, the energy differential measurement requires the detection of protons coming directly from the reaction. In order to reach the intended high neutron energies the measurement has to be performed in Experimental Area 1, featuring a ∼10 times longer flight path than the Experimental Area 2.
The main reason for the cross section of the ^{12}C(n,p) reaction to be so uncertain is related to the experimental challenges in performing the energy differential measurement. If the sample itself does not act as the detector (as in the case of previous measurements with diamond detectors), the measurement must satisfy the following: (1) it must be performed in vacuum to avoid the energy loss of protons in air, which also acts as source of background through competing $(n$,cp) reactions; (2) the detector needs

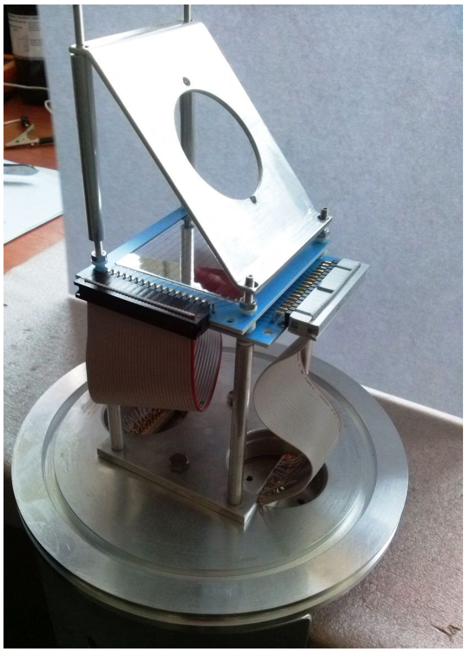

Figure 3: Silicon telescope proposed for the ^{12}C(n,p) measurement.

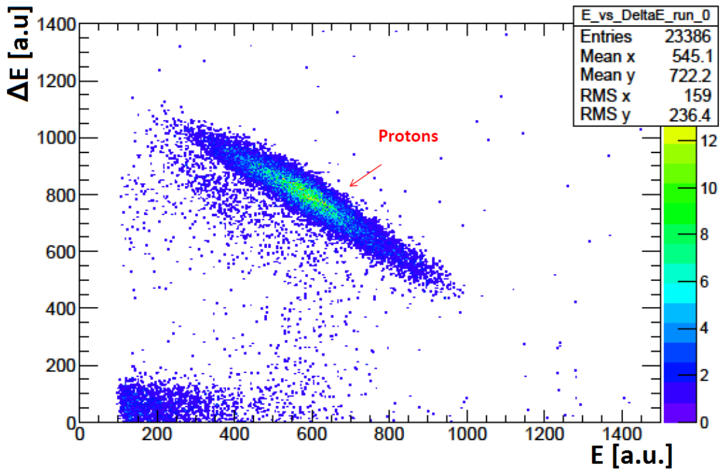

Figure 4: Experimental data from the ^{7}Be(n,p) campaign, acquired with the silicon telescope proposed for measurement of the ^{12}C(n,p) reaction.

to be out of beam, otherwise it is a source of background itself and the γ-flash signal may prevent going to high energy; (3) a telescope configuration is required in order to distinguish protons from other particles. All of these challenges are met by the silicon telescope (Fig. 3), which was successfully used at n_TOF for the challenging measurement of the ^{7}Be(n,p) reaction [10], related to the Cosmological Lithium Problem. Figure 4 shows the experimental data from the ^{7}Be(n,p) campaign, clearly demonstrating the capability of the system to discriminate the protons by ΔE–E correlations. Another advantage of this system is that both Silicon layers are made of 16 strips, allowing a rough estimate of the angular distribution in the range covered by the telescope (approx. 60°–120°). In order to obtain additional information on the angular distribution at forward and backward angles, we are considering mounting in the same chamber two small single-pad telescopes, already available, with a minor modification of the mechanical support.

The proposed measurement with this setup is limited to energies below ∼25 MeV because at higher energies protons created by the ^{12}C(n,p) reaction can not be distinguished from protons coming from competing reactions. As the evaluated cross sections from Fig. 5 show, the ^{12}C(n,np) reaction opens already at 20 MeV and rapidly dominates the ^{12}C(n,p) reaction. Based on the difference between the energy deposition from the ^{12}C(n,p) protons and ^{12}C(n,np) protons produced near the reaction threshold, we expect that ^{12}C(n,p) protons should be distinguishable up to 25 MeV, allowing to cover the peak of the cross section (Fig. 1).

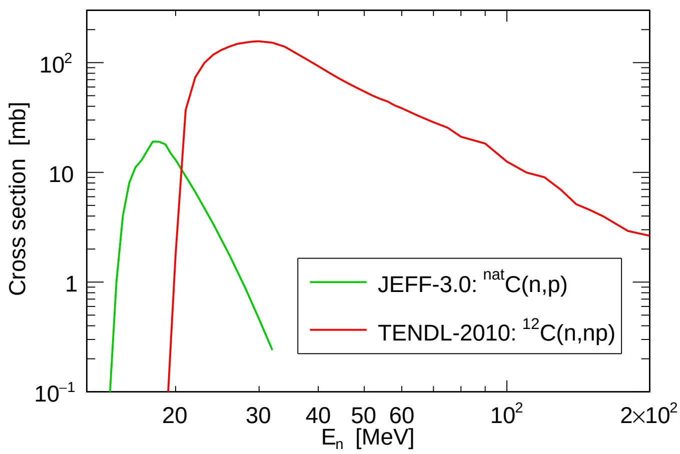

Figure 5: Evaluated cross sections for the ^{12}C(n,p) and the ^{12}C(n,np) reaction from available libraries.

The simulations indicate that the optimal thickness of the carbon sample is approximately 0.2–0.3 mm, as the best compromise between the maximization of the proton yield and the minimization of the multiple scattering background. It should be noted that the simulations assume that the reaction residue is produced in its ground state. In reality, the first excited levels of ^{12}B can also be populated in the reaction. In this case the protons are emitted with a lower energy and may fall below the identification threshold. Although at the lowest energies only a partial cross section will be determined, the total cross section will be calculated taking into account the experimental and/or theoretical branching ratios, similarly to the method used in the recent measurement of the ^{7}Be(n,α) reaction [11].

3 Required beam time

As there are no consistent or reliable evaluations of the ^{12}C(n,p) cross section, the estimates of the required beam time are subject to some uncertainty. An estimate of the count rate and of the detection efficiency has been obtained by means of GEANT4 simulations considering different models, in particular Binary, Bertini and INCL++ cascade. Considering that the Binary cascade model predicts the reaction yield closest to the integral n_TOF value (Fig. 2), we will present here only its results. Figure 6 shows the expected ^{12}C(n,p) count rate per single neutron pulse. The detection becomes appreciable at energies ∼1 MeV above the reaction threshold. The discontinuity visible in the spectra is an artifice of the Binary cascade model, which was not observed in other models. In addition, it may be noted that in this model the reaction threshold is around 15 MeV instead of the expected 13.6 MeV. Similar threshold deviations were also observed with other models, but they are not relevant for the n_TOF measurement, since the analysis of the experimental data will not rely on these simulated results.

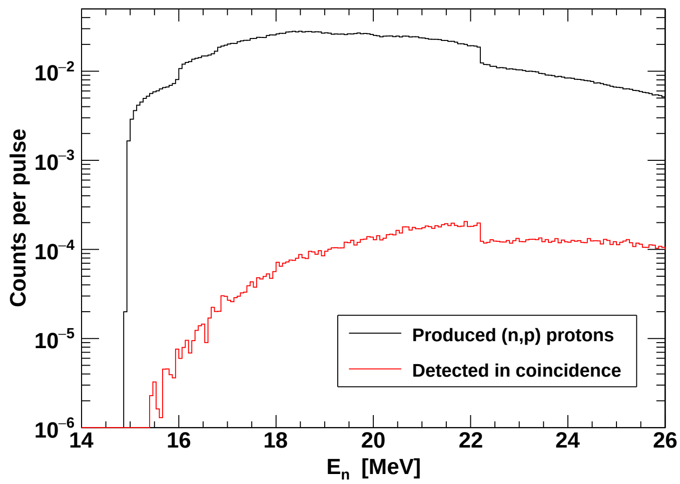

Figure 6: Proton production and detection rate per neutron pulse, according to the full simulation of the proposed experiment with the Binary cascade model.

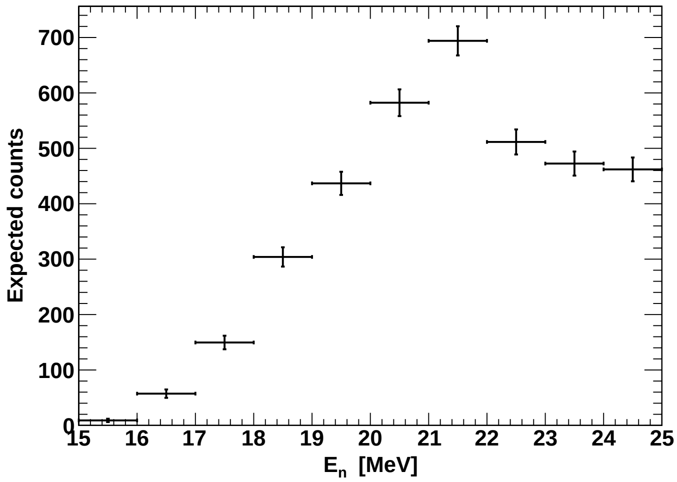

Figure 7: Expected number of counts (1 MeV bin width) with 1.75×10^{18} protons on target, according to the Binary cascade.

For the cumulative number of counts up to 25 MeV the Binary cascade predicts 0.0145 counts/pulse, equivalent to 2000 counts per 10^{18} protons (500 counts per day, assuming the average of 2.4 s between proton pulses), without any thresholds on the deposited energy. Thus, we request in total 2×10^{18} protons on target to reach a statistical uncertainty of less than 10% in each bin, for 10 bins between 15 and 25 MeV neutron energy. Figure 7 shows the expected number of counts (bin width of 1 MeV) assuming 1.75×10^{18} protons allocated to the measurement with the sample in place. The remaining 0.25×10^{18} protons will be needed for the measurement of the background with an empty sample, expected to be small in this measurement.

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