Measurement of the energy-differential cross section of the ^{12}C(n,p) and ^{12}C(n,d) reactions

Proposal to the INTC

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Motivation

Importance of the ^{12}C(*n,p*) and ^{12}C(*n,d*) reactions:

- **dose estimation in radioprotection and hadrontherapy**
- **design of shields and collimators at accelerator facilities, spallation sources and irradiation facilities for fusion materials**
- **response of the diamond detectors to fast neutrons**
- **understanding of the nuclear structure of light nuclei**

  When the theoretical parameters are adjusted so as to reproduce the measured (n,p) cross section, the (n,d) one is predicted to be significantly higher than expected from the general theoretical considerations. This relation may be the signature of nontrivial effects in light nuclei.

Time-of-flight measurement

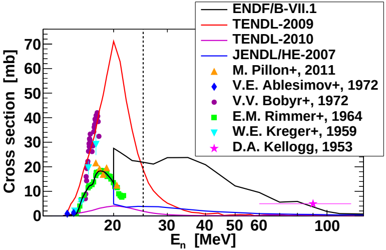
Main consideration regarding the activation measurement with a quasimonoenergetic neutron source: a short half-life of ^{12}B (20 ms).

- **an on-line technique required (as at n_TOF) since ^{12}B can not be built-up for a prolonged measurement**
- **pulsed neutron source required in either case (activation or ToF), with a very low duty cycle ($<$10 Hz)**
- **in addition, a proposed measurement at n_TOF makes for an independent experiment which brings a methodological novelty to the investigation of these reactions**

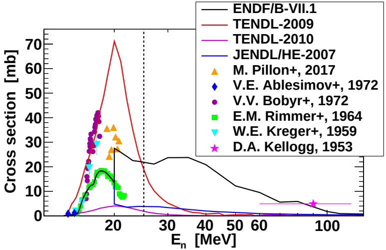
Status overview of ^{12}C(n,p)

Subject under persistent investigation by Pillon et al.

Pillon et al., 2011



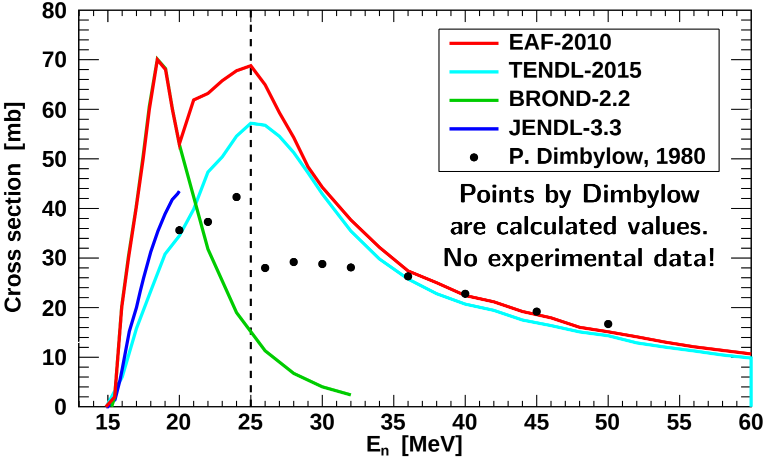
Pillon et al., 2017



- **highly uncertain cross section throughout evaluated libraries, experimental data and between different models**
- **the latest integral measurement from n_TOF indicates that Rimmer's data (on which major evaluations are currently based) are wrong, while supporting the data from Bobyr and Kreger**

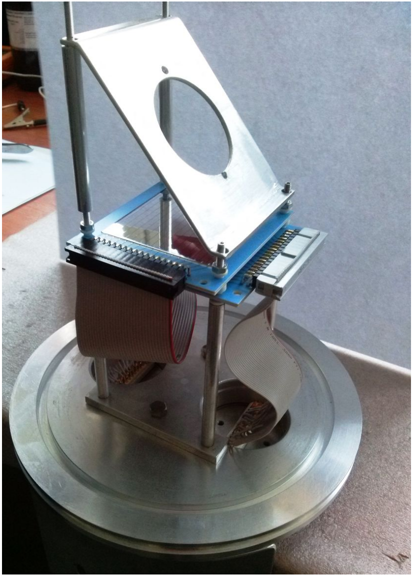
Status overview of ^{12}C(n,d)

The most pronounced discrepancies precisely below 25 MeV!

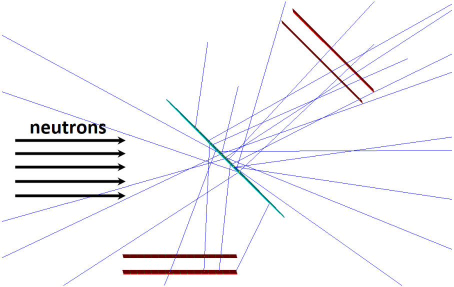


The peak of EAF-2010 for (n,d) at 70 mb, the same as TENDL-2009 for (n,p) [see previous slide] $\Rightarrow$ similar statistics expected for both reactions.

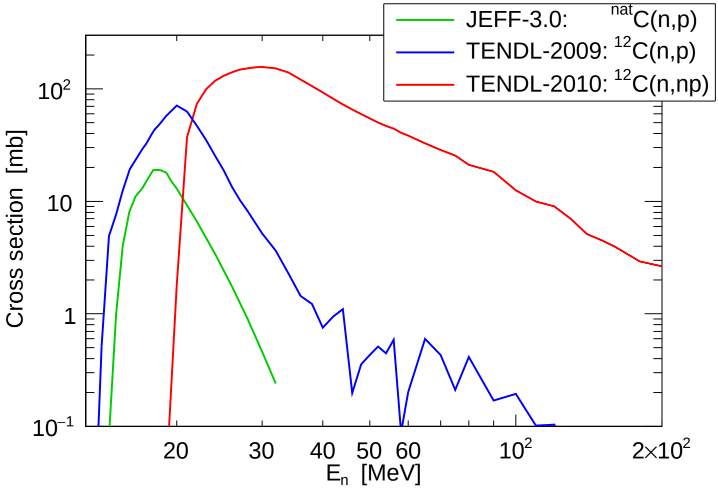
Proposed experimental setup



Intended use of the updated, geometrically optimized setup, comprising double the number of channels/Si-strips (64 in total) and featuring a very wide angular coverage ($10^\circ - 150^\circ$).

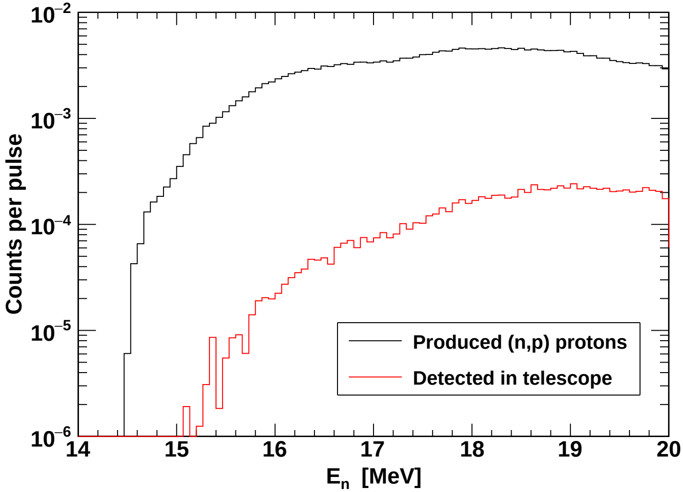


Expected (*n,p*) discrimination: up to 25 MeV



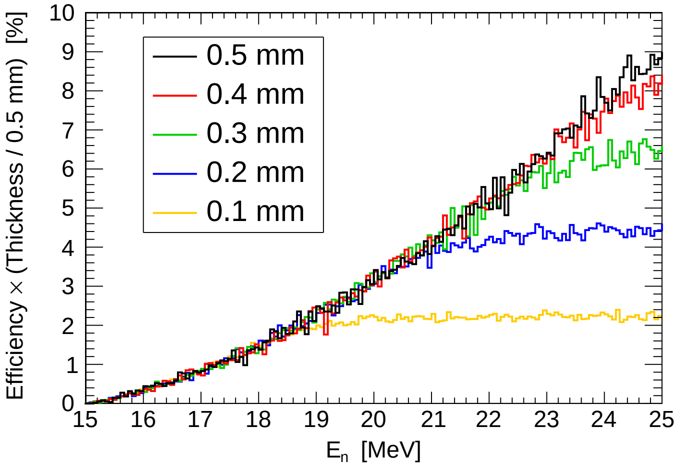
Above 25 MeV the proton yield from the ^{12}C(*n,np*) reaction is expected to start mixing with the ^{12}C(*n,p*) yield.

Distance to threshold: ∼1 MeV



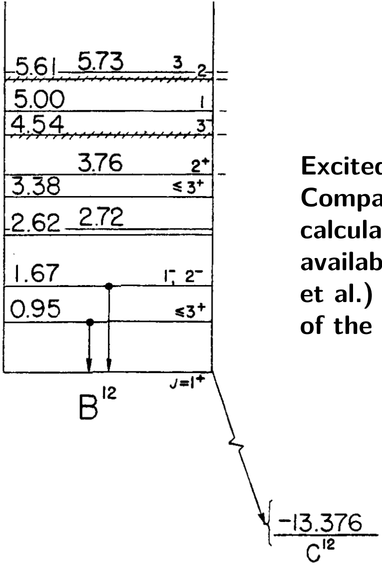
Detected counts reduced due to the limited solid angle, i.e. the geometrical efficiency (no ENDF data above 20 MeV).

Sample thickness: 0.2–0.3 mm



0.2–0.3 mm: the optimum between the detected reaction yield up to 25 MeV and the background induced by the secondary reactions.

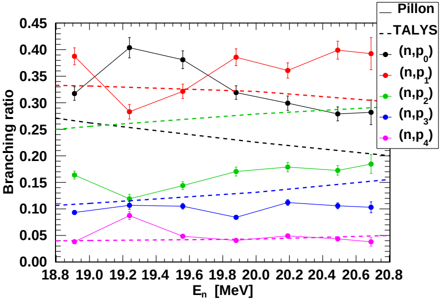
Excited states and angular distribution

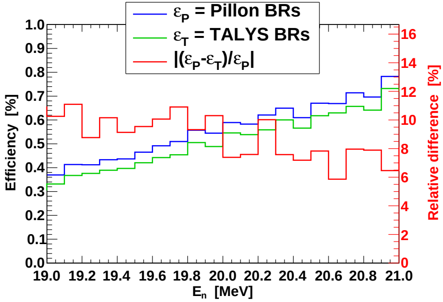


Excited states of ^{12}B are known! Comparison between the theoretical calculations (e.g. TALYS) and the available experimental data (e.g. Pillon et al.) as the basis for the estimation of the systematic uncertainties.

Uncertainty due to branching ratios

Based on the difference between the detection efficiencies obtained assuming either the experimental branching ratios by Pillon et al. (data available for 5 lowest states) or theoretical branching ratios calculated by TALYS.



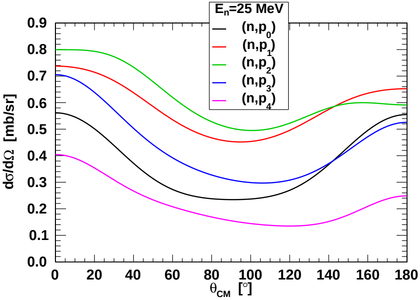


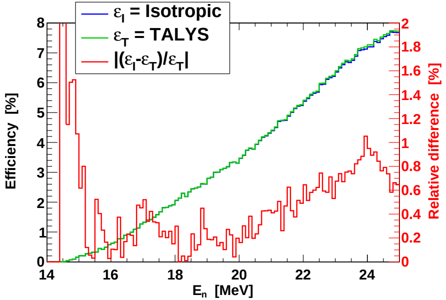
Within the energy range of the available experimental data, this contribution to the systematic uncertainty is limited to **10%**.

Uncertainty due to angular distributions

Based on the difference between the det. effs. obtained either from the isotropic proton emission or angular distributions from TALYS.

Notice: TALYS predicts the forward-focusing of high-energy protons, in accordance with the experimental data from Subramanian et al.

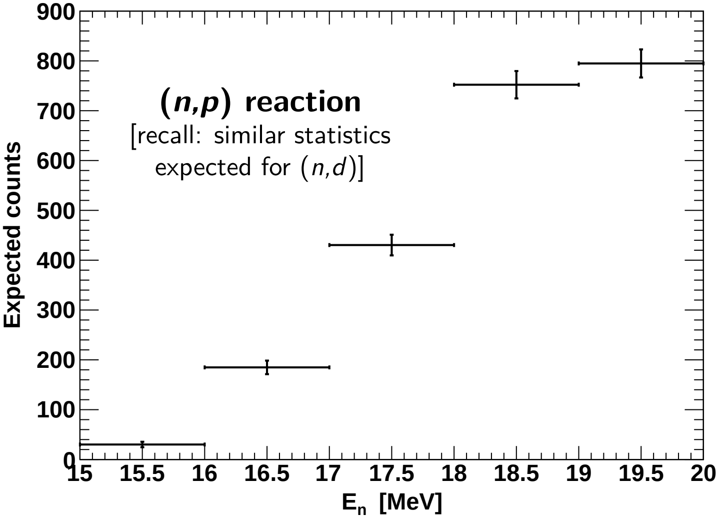




This contribution to the systematic uncertainty is mostly limited below **1%**, due to the wide angular coverage of the optimized geometrical setup.

Proposed number of protons: 2×10^{18}

(ENDF data only up to 20 MeV)



Conclusions

- **the data on the ^{12}C(*n,p*) and the ^{12}C(*n,d*) reaction are, at present, largely discrepant, between experiments, models and evaluations**
- **the latest integral measurement from n_TOF suggests that none of them are quite reliable**
- **we propose an energy-differential measurement up to 25 MeV, to be performed by detecting the protons from the ^{12}C(*n,p*) and deuterons from the ^{12}C(*n,d*) reaction**
- **the challenges will be met by using a high-end stripped Si-telescope with a wide angular coverage, in combination with the advanced data analysis**
- **systematic uncertainty expected at the level of 10%**

  10% uncertainty does not only allow to discriminate the sets of data differing by factor of 5. It can validate or invalidate a methodology used in some evaluations, such as ENDF, which consists of relying on a very limited set of measured data, without considering the consistency of the different channels such as (*n,p*), (*n,d*), etc. In this respect, our claimed accuracy is clearly meaningful.
- **we ask for the total of 2×10^{18} protons on target**

Thank you for your attention!

Backup slide

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Calculation and Evaluation of Cross Sections and Kerma Factors for Neutrons up to 100 MeV on Carbon

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Abstract – *We present an evaluation of the interaction of neutrons with energies between 20 and 100 MeV with carbon nuclei. Our aim is to accurately represent integrated cross sections, inclusive emission spectra, and kerma factors, in a data library for use in radiation transport simulations of fast neutron radiotherapy. We apply the Feshbach-Kerman-Koonin-GNASH nuclear model code, which includes Hauser-Feshbach, pre-equilibrium, and direct reaction mechanisms, and use experimental measurements to optimize the calculations. We determine total, elastic, and nonelastic cross sections; angle-energy-correlated emission spectra for light ejectiles with $A \leq 4$ and gamma rays; and average energy depositions. Coupled-channel optical model calculations describe the total, elastic, and nonelastic cross sections well. Our results for charged-particle emission spectra agree fairly well with University of California–Davis as well as new Los Alamos National Laboratory and Louvain-la-Neuve measurements. We compare our results with the recent ENDF/B-VI evaluation and argue that some of the exclusive channels between 20 and 32 MeV should be modified. We also compare kerma factors derived from our evaluated cross sections with the measurements, providing an integral benchmark for our work. The evaluated data libraries are available as electronic files.*

I. INTRODUCTION

A number of new applications, such as radiation transport simulations of cancer radiotherapy and the accelerator-driven transmutation of waste, require evaluated nuclear data libraries when modeling the interaction of neutrons above 20 MeV (Ref. 1). The major efforts in nuclear data evaluation work over the last few decades have concentrated on reactions below 20 MeV for fission and fusion applications. Above this energy, transport calculations have been generally performed with codes that calculate nuclear cross sections on an event-by-event basis using intranuclear cascade (INC) methods. However, the underlying physical assumptions of the INC theory are not well satisfied below 100 MeV, and there is a need to extend evaluated nuclear data libraries up to higher energies. Furthermore, evaluated libraries can represent the physical interactions more accurately because they can be based on experimental measurements in addition to model calculations. Our

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Most modern fast neutron therapy facilities use a ^{9}Be(p,n) source reaction, which produces a broad spectrum of neutrons with energies up to 70 MeV. (...) With the exception of hydrogen, sufficiently accurate nuclear data do not yet exist in this energy range to allow neutron therapy to reach its full potential. Because "standard man" consists (by mass) of hydrogen (10%), carbon (18%), nitrogen (3%), oxygen (65%), and various trace elements (4%), an accurate understanding of neutron nuclear reactions on carbon is essential.

M. B. Chadwick et al.
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