EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the Double-Differential Cross Section of Neutron-Induced Charged-Particle Emission of Carbon from 20 MeV to 200 MeV

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R. Beyer [1], M. Dietz [2], A. R. Junghans [1], R. Nolte [2], E. Pirovano [2], S. Pomp [3], D. Tarrío [3], P. Vaz [4], and the n_TOF Collaboration

[1] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Bautzner Landstraße 400, 01328 Dresden, Germany
[2] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[3] Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[4] Centro de Ciências e Technologias Nucleares (C2TN), CTN - Estrada Nacional 10; 2965-066 Bobadela LRS, Portugal

Spokesperson(s): E. Pirovano (elisa.pirovano@ptb.de), R. Beyer (roland.beyer@hzdr.de)
Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

Abstract

High-energy neutrons produced as stray radiation in high-energy accelerators or as secondary radiation by cosmic rays are a concern for radiation protection, and in hadron therapy centers, they must be included in the radiation treatment planning. Double differential cross section (DDX) data on the neutron-induced emission of light charged particles energy up to several hundreds of MeV are therefore necessary for kerma factors and dose calculations. The objective of the proposed experiment is to investigate the feasibility of DDX measurements at n_TOF. The proposal focuses of the measurement of the DDX of carbon, as one of the main human-tissue constituents, up to 200 MeV in neutron energy, which is the range of interest for proton radiation therapy. With the proposed prototype setup and 3×10^{18} protons on target is should be possible to achieve the same statistical uncertainties for earlier experiments.

Requested protons: 3×10^{18} protons on target, (in 1 run over 1 year)
Experimental Area: EAR1

Objectives and motivations

High-energy neutrons produced as stray radiation in high-energy accelerators, or as secondary radiation by cosmic rays, are a concern for radiation protection, radiation treatment planning, and can cause instrumentation damage. In hadron therapy, for example, secondary neutrons with energies up to about 200 MeV (proton beams) [1] or 400 MeV (carbon ion beams) [2] are produced by beam interaction in the treatment head and in the target volume. The risk of secondary tumors induced by these neutrons has received increased interest recently [3,4], in particular for young patients. The risk assessment is based on the calculation the absorbed dose from the neutron fluence, and the required kerma factors are calculated from double-differential cross sections (DDX) for the emission of light charged particles. This approach is also used to investigate radioprotection issues also in other contexts, for example to determine the health risk associated to space travel [5,6], which will get increased awareness with the present consolidation of plans to set up a permanent habitat on the lunar surface.

The experimental DDX data for tissue constituents are still rather scarce for neutron energies above 20 MeV. Data were measured only for incident neutrons with energies up to 100 MeV; and close to 100 MeV there are only very few DDX data sets available for carbon [7,8,9] and oxygen [10,11]. On the other hand, the calculation of DDX data using statistical, quantum mechanical or intranuclear cascade (INC) models is difficult for low-mass nuclei and composite ejectiles [12]. Due to the large neutron energy range and the relatively small DDX values (usually less than 1 mb/(sr MeV) for $Z = 1$ ejectiles even at forward angles), evaluated data bases cannot be constructed from experimental data alone. Instead, nuclear model calculations [13] must be used. Therefore, benchmarking and improvement of codes is important in the energy region between 100 MeV and 200 MeV, where the statistical model becomes insufficient, and the INC model just starts to become applicable. This requires experimental data at selected forward and backward angles which test the description of the intranuclear cascade and de-excitation phases of the interaction. Data for the neutron-induced emission of helium ions would be of particular importance, as complex ejectiles are not generically described in the INC model but require the ad hoc addition of a coalescence model [12].

The objective is therefore to investigate the feasibility of double-differential cross section measurements at n_TOF, to produce data of interest in first instance for proton therapy. This proposal is dedicated to the measurement of the DDX of the neutron-induced charged-particle emission of carbon. The experiment will focus on the energy range between 100 MeV and 200 MeV, which is largely unexplored, and on the emission of hydrogen and helium isotopes. In contrast to the quasi-monoenergetic sources used for earlier works, a continuous coverage of the relevant neutron energy range could be achieved. Therefore, the setup should be installed in the Experimental Area 1 (EAR1), as its 185-m long flight path is essential to resolve high-energy neutrons using the time-of-flight technique. Considering the low cross section values, the goal is to prove the feasibility and to obtain at least the same statistical uncertainties as previous measurements at 100 MeV.

In the Letter of Intent (LOI) submitted in September 2022 [14], beamtime was requested for detector development. The intense γ-flash produced by the spallation target of n_TOF was expected to be a challenge. The test beamtime was fundamental in determining a working configuration for detectors and readout electronics that allows the identification of charged particles produced by high-energy neutron-induced reactions on graphite. A longer measurement is now necessary to collect enough statistics to determine the constraints of neutron-energy dependent DDX measurements at n_TOF.

Proposed experimental setup

The experimental setup currently under consideration is shown schematically in Fig. 1. It consists of three detector telescopes pointed at a graphite sample irradiated by the neutron beam, and positioned at the emission angles of 20, 60 and 120 degrees. Each telescope is composed of two silicon diodes that act as transmission detectors (also referred as "ΔE detectors"), and a stop detector (or "E detector") which can be either an EJ-204 plastic scintillator or a $CeBr_3$ scintillator. The graphite sample and the silicon diodes are placed in a vacuum chamber to reduce the energy loss between ion production and detection. The scintillators are installed outside the chamber, behind thin windows, to allow easy readout of the scintillation detectors using photomultiplier tubes (PMTs).

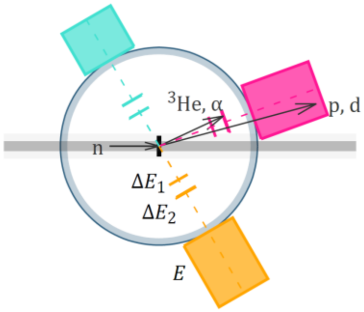

Fig. 1: Schematic representation of the experimental setup for the DDX measurement. Three particle telescopes, pointed at a graphite sample, are installed at the emission angles of 20, 60 and 120 degrees. Each telescope is composed of two silicon diodes (ΔE_1 and ΔE_2 detectors) and a scintillator (E detector). The graphite sample and the silicon diodes are mounted inside a vacuum chamber, while the scintillators (and corresponding PMTs) are in air.

The principle of operation consists in requiring coincident signals for at least two of the three detectors, to identify the particles emitted by the graphite sample in a given direction. The ΔE-E technique is then used to discriminate protons, deuterons, tritons, and alpha particles. The detector dimensions are such that the solid angle is determined by the size of the second ΔE detector, while the length of the scintillators must be enough to fully stop protons of 200 MeV.

The silicon diodes procured for this experiment are quadratic detectors with an active area of 900 mm^2 and a thickness ranging from 50 μm to 1000 μm. They are mounted on a small printed-circuit board frame, which allows to use them as transmission detectors. The stop detector at 20° is a cylindrical $CeBr_3$ scintillator of 3" diameter and 2" length. At larger angles EJ-204 plastic scintillators of 8 cm diameter and 10 cm or 15 cm length are used.

For the tests, an existing scattering chamber was adapted to the technical constraints at n_TOF EAR1 (see picture in Fig. 2). The light-weight aluminum chamber has a diameter of 400 mm and a height of 150 mm, and it is equipped with eight 47-mm diameter flanges with an angular separation of 45 degrees. Four flanges held signal feedthroughs; the other four were replaced with windows, of 50 µm Kapton and 200 µm aluminium, for the ingoing and outgoing neutron beam, and for two full ΔE_1-ΔE_2-E telescope arms at 45 degrees relative to the beam direction. The chamber was accompanied by a SCROLLVAC pump which reaches a residual gas pressure of about 1 Pa – 10 Pa, which is lower than what is required for the purpose.

The position of the telescopes in the test chamber was bound to that of the Kapton windows; that is why they did not match the emission angles considered for the final experiment. For the carbon measurement, a new chamber is therefore necessary. The design however will be similar in dimensions and materials to the test chamber, as in the n_TOF EAR1 the physical space is limited and equipment for handling heavy devices is not available.

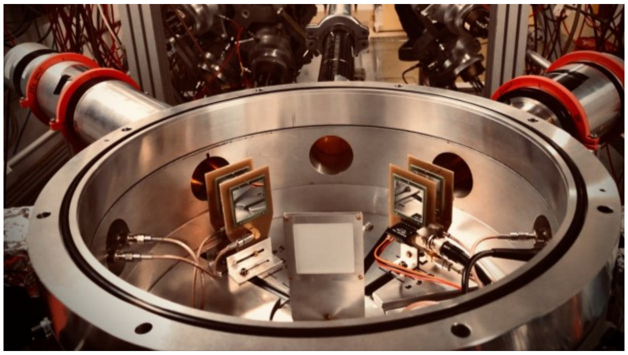

Fig. 2: Picture showing the detectors and a polyethylene sample mounted inside the vacuum chamber used for the detector test, installed in the EAR1 of n_TOF. The vertical axis of the picture (from the bottom to the top of the picture) corresponds to the neutron beam direction. The silicon diodes on the left side of the polyethylene sample are connected to Cividecs Cx-L preamplifiers, which are installed outside the chamber (not captured in this photo). On the right side, the first diode (ΔE_1) is connected to a Cremat CR110 preamplifier, which is mounted on the printed-circuit board frame, directly under the diode. The second diode (ΔE_2) is connected to a Canberra 2004 preamplifier, installed outside the chamber. The two detectors behind the vacuum chamber are a 150 mm long EJ204 plastic scintillator (on the left) and a 76.2 mm long $CeBr_3$ scintillator (on the right).

For the normalization to the incident neutron fluence, a low-mass fission chamber equipped with eight ^{235}U samples, already successfully employed in previous experiments in the same energy range [15] and for the third-generation target commissioning [16], will be used. The chamber will be upgraded by integration of the preamplifiers into the chamber housing. This will reduce the sensitivity to electromagnetic interference which impaired the use of the fission chamber at high neutron energies in the past.

Results from the detector test beamtime

The main goal of the beamtime dedicated to detector development was testing silicon diodes of different thicknesses coupled with different models of charge-integrating preamplifiers, to verify if the energy resolution was sufficient to separate hydrogen isotopes and helium isotopes in the ΔE-E two-dimensional histograms. The intense γ-flash at EAR1 was expected to be the main challenge, as in earlier measurements it was found to partially exhaust the dynamic range of the preamplifier, consequently leading to loss of valid events due to early saturation.

With the prototype setup, the γ-flash did not pose a problem in itself, however it did significantly disturb the data acquisition, as it was found to be associated to electromagnetic noise that produced oscillations in the preamplifier readout signal with amplitudes comparable to the pulse height of particle-induced events. The origin of these electromagnetic interferences in the radiofrequency (RF) range, and their relationship to the γ-flash, has not been fully understood but it is also currently under investigation at CERN [17].

The test of different signal amplification configurations resulted in several observations. At n_TOF, excellent shielding against electromagnetic interferences is needed early on in the signal chain. Therefore, the scattering chamber, including the windows, must be RF-tight, but also the preamplifier modules needed additional shielding including all cable connections in between, which are already kept as short as possible. Special capacitance-matched preamplifiers for the thinnest diodes like Ortec 142C or Mesytec MPR-1 performed worse than Cividec Cx-L series and Cremat CR110. The benefit of the Cremat modules is the usage inside the vacuum chamber, which leads to the best, almost fully suppressed oscillations in the baseline.

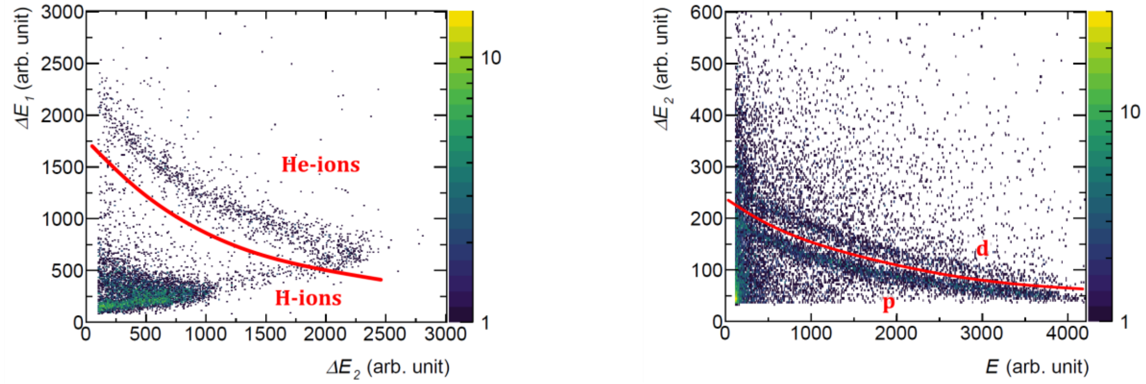

Fig. 3: Two-dimensional histograms showing the ΔE_1-ΔE_2 (left panel) and ΔE_2-E (right panel) event distributions recorded in about 2.5 days of beamtime using a graphite sample. These events correspond to neutron energies from 5 MeV to 200 MeV. The ΔE_1-ΔE_2 distribution was used to separate the helium ions from hydrogen ions, the ΔE_2-E for the separation of protons from deutrons. It was not possible to observe tritons as the emission probability is very low.

With the best test configuration using Cividec and Cremat preamplifiers, data produced with a carbon sample were collected over about 2.5 days, and promising particle separation results were produced. Fig. 3 (left panel) shows the ΔE_1-ΔE_2 histogram using Cremat preamplifiers with good separation between hydrogen and helium ions. The right panel of Fig. 3 illustrates in a ΔE_2-E histogram the separation between protons and deuteron using a 1000 µm diode with a Cividec module and a 150 mm plastic scintillator with PMT as E-detector. It should be noted that these fresh data result from a run in November 2022. The pulse-height thresholds and coincidence conditions are not yet optimized. Moreover, the histograms comprise the full neutron energy range from 5 MeV to 200 MeV. With improved pulse-shape and event identification analysis, it should be possible to reduce the number of background events outside of the regions for valid p, d and α events.

In summary, the detector test beamtime demonstrated that with the proposed setup it is possible to identify emitted protons, deuterons and helium ions up to about 200 MeV of incident neutron energy. The number of recorded events however is too low to study the ejectile energy distributions; therefore to complete this proof-of-principle experiment it is now necessary to request a longer beamtime.

Expected performance and beam time request

The expected count rates, and the energy distributions of the emitted particles, have been calculated using the ICRU DDX data [13] for incident neutron energies below 150 MeV, and the INCL intranuclear cascade model for energies above 150 MeV. Since the results of the third-generation target commissioning are not final yet, the evaluated neutron flux of the second-generation target [18] was used. This should be a conservative assumption, as with the third-generation target, the neutron flux in EAR1 should be comparable or higher than that obtained with the second-generation target.

With the detectors available at present, it is possible to build three triple-stage particle telescopes, one for each of the three considered angles, at 20, 60 and 120 degrees. In the configuration under consideration, the ΔE_2 detectors, which define the telescope solid angle, are placed at a distance from the center of the graphite sample of 20 cm. This corresponds to an angular acceptance of ±4.3 degrees, which was chosen as a compromise between angular resolution and geometrical efficiency.

For the carbon experiment, two graphite samples of 50 μm and 2 mm thickness, respectively, are being considered. The thick sample will be used to collect statistics, therefore most of the beamtime will be dedicated to its irradiation. The thin sample will be used to study systematic effects due to the particle energy loss inside the graphite sample, to collect data for testing the data analysis procedures which will be necessary to correct the shape of the lower part of the ejectile energy distributions.

To obtain low statistical uncertainties on the ejectile energy distributions (e.g., below 20% per energy bin), the beamtime request would exceed 10^{19} protons on target, which is unreasonable for a proof-of-principle experiment. For this reason, the objective has been reassessed to attaining similar statistical uncertainties as those achieved in earlier experiments, at least at the most forward angle of 20 degrees. This can be achieved with 25×10^{17} protons on target and the 2 mm carbon sample. Additional 5×10^{17} protons are requested to irradiate the 50 μm sample, to investigate potential systematic effects due to the sample thickness.

As an example, Fig. 4 shows the ICRU DDX data for the emission of protons and alpha particles for a neutron energy bin of (100 ± 5) MeV, together with error bars representing the statistical uncertainty per ejectile energy bin. The figures for deuteron emission are similar to those shown for proton emission. The expected relative statistical uncertainties are compared to that reported in EXFOR for the experiment carried out at the TSL neutron beam facility in Uppsala (Sweden) using quasi-monoenergetic neutrons of 98.5 MeV [7].

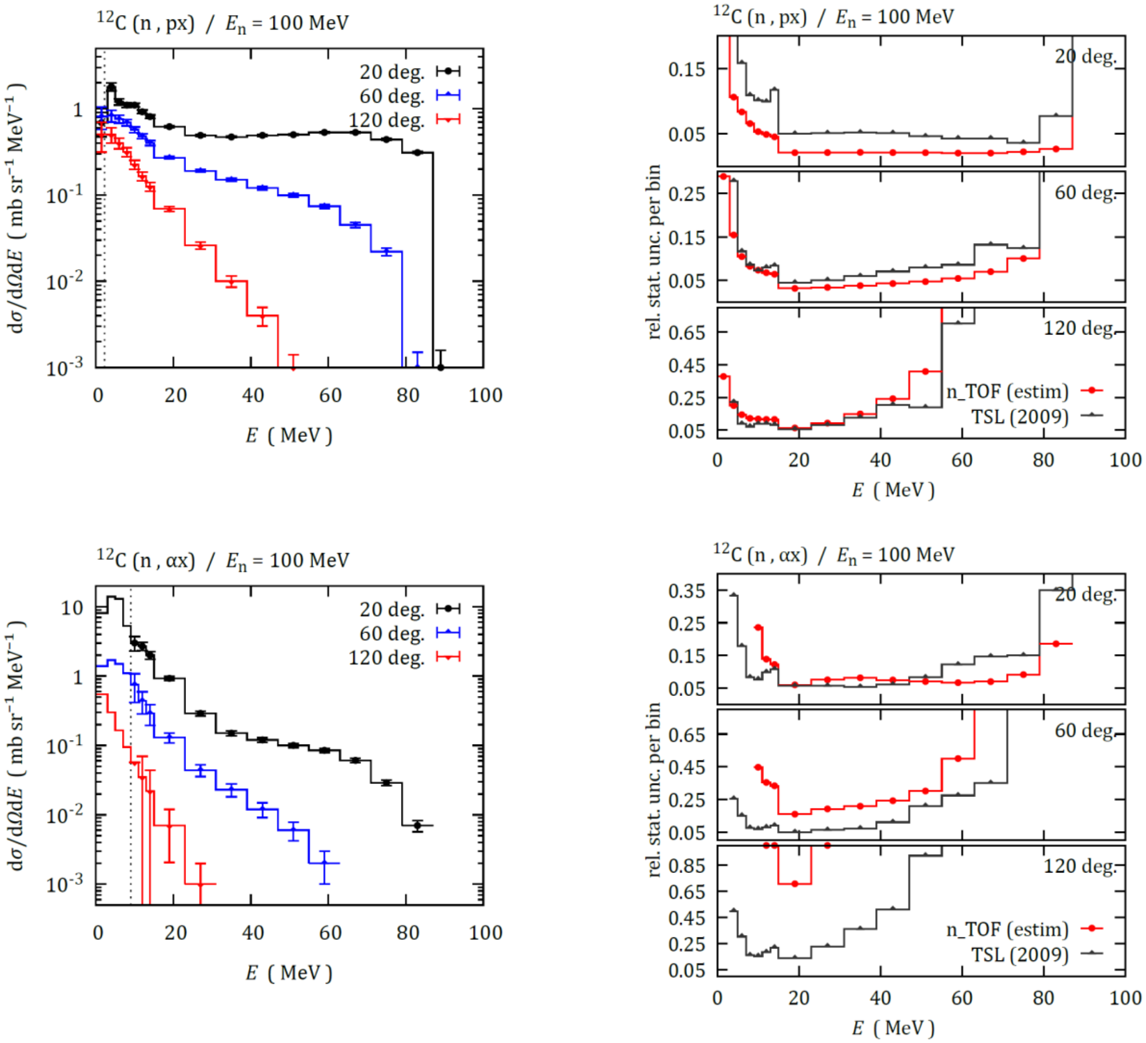

Fig. 4: The panels on the left side show the ^{12}C DDX data for protons and α-particles at 100 MeV of incident neutron energy. The cross-section data are taken from [13]. The error bars indicate the expected statistical uncertainty per energy bin for the proposed experiment. The dotted line represent the lowest detected ejectile energy. The right-side panels present a comparison with the uncertainty achieved at the TSL facility [7], as reported in EXFOR. To facilitate a comparison, the uncertainties of the TSL DDX data were re-binned to the bin structure of the ICRU DDX data assuming statistical uncertainty contributions only.

With the proposed prototype experiment, statistical uncertainties comparable to those of existing datasets could be achieved at all angles for the emission of hydrogen ions. The cut-off energies, however, would be higher than those achieved at TSL. For alpha particles, the same could be achieved only at the emission angle of 20 degrees. At 60 degrees the uncertainties would be around 30%, while at 120 degrees the energy distribution is unlikely to be determined. Nevertheless, if successful, this would be a first-of-its kind experiment at n_TOF, and it could pave the way for more complex setups, with more detectors and therefore higher efficiency, and more ambitious experimental campaigns.

Summary of requested protons:

3×10^{18} protons on target in 1 run.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using [Name fixed/present n_TOF installation: e.g. TAC, C6D6, SIMON, uMegas, HPGe, GEAR-HPGe]	☐ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute [DDX vacuum chamber]	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
[Flux monitor: low-mass ^{235}U fission chamber]	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☒	DDX vacuum chamber: 10^{-1}–10^{-2} mbar
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m^3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]

	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			