HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection 2018 (NFRP-2018-4)

Project acronym:	**SANDA**
Project full title:	**Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities**
Grant Agreement no.:	**H2020 Grant Agreement number: 847552**

Workpackage N°:	***WP2***
Identification N°:	***D2.10***
Type of document:	***Deliverable***
Title:	Report on the measurement of double-differential charged-particle emission cross sections at the CERN n_TOF facility in the neutron energy range from 20 MeV to 200 MeV
Dissemination Level:	***PU***
Reference:	
Status:	***VERSION 1***
Comments:	

	Name	Partner	Date	Signature
Prepared by:	E. Pirovano	22	10-06-2024	
WP leader:	D. Cano-Ott	1	10-06-2024	Firmado por CANO OTT DANIEL - DNI ***8222** el día 01/07/2024 con un certificado emitido por AC Sector Público
IP Co-ordinator:	E. González	1	10-06-2023	Signed by GONZALEZ ROMERO ENRIQUE MIGUEL - DNI ***3708** at 01/07/2024 with a certificate isued by AC Sector Público

Report on the measurement of double-differential charged-particle emission cross sections at the CERN n_TOF facility in the neutron energy range from 20 MeV to 200 MeV

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Abstract

This report describes the progress on the project for the development of an experimental setup for the measurement of double-differential cross sections of neutron-induced charged particle emission at CERN n_TOF for energies up to 200 MeV and its application on the case of carbon (Subtask 2.6.2). Two tests were performed at n_TOF to investigate the interaction of the detectors with the γ-flash and to investigate possible solutions to suppress its effect. The results were analysed to prepare an exploratory measurement on carbon aimed which was performed in September 2023. The preliminary results are compared with data from the ICRU evaluation and the INCL model.

1. Introduction

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 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. Risk assessment calculations are based on 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 (cp). This approach is also used in other contexts, for example to determine health risks associated to space travel [5,6], which are also getting increased attention 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 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 is also particularly significant, as complex ejectiles are not generically described in the INC model but require the ad hoc addition of a coalescence model [12].

The objective of this project is therefore to investigate the feasibility of double-differential cross section measurements at CERN n_TOF [13], the only neutron source in Europe able to provide neutrons with energies above 100 MeV. The work consists in the development of a proof-of-principle experiment for the measurement of the DDX of neutron-induced charged particle emission of carbon, with focus is on the energy range between 100 MeV and 200 MeV and on the emission of hydrogen and helium isotopes.

The conceptual design of the experimental setup is shown schematically in Figure 1. It consists of three particle telescopes pointed at a graphite sample irradiated by the neutron beam. The detectors are 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 plastic or inorganic scintillator acting as stop detector (or "E detector"). 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). The incident neutron flux is monitored using a Parallel Plate Fission Chamber (PPFC) containing ^{235}U. This setup is to be installed at the n_TOF Experimental Area 1 (EAR1) [14], as its 185-m long flight path is essential to resolve high-energy neutrons using the time-of-flight technique.

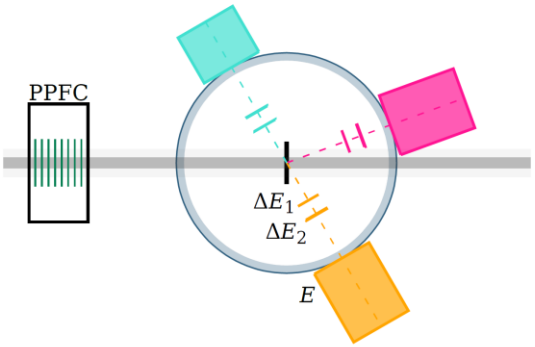

Figure 1: Schematic representation of the experimental setup for the C(n,cp) DDX measurement at the EAR1 of n_TOF. Three particle telescopes, pointed at a graphite sample, are installed at the emission angles of 20, 60 and 120 degrees. Each telescope is composed of two silicon diodes (ΔE_1 and ΔE_2 detectors) 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 incident neutron flux is monitored using a Parallel Plate Fission Chamber (PPFC) containing ^{235}U placed upstream the chamber.

2. Status of the project at the completion of the SANDA Task 1.4

Within SANDA, this project is divided in two tasks: Task 1.4, dedicated to the development of the experimental setup, and Subtask 2.6.2, focused on the measurements of the double differential cross sections for the charge particle emission on carbon at n_TOF. Task 1.4 was formally completed in February 2022 with the submission of the deliverable D 1.8, "Report on the development and performances of the new detectors for non-energy applications". Subtask 2.6.2 started immediately thereafter.

In this section, the status of the project at the time of the transition between tasks is briefly summarized; the details on the experimental and data analysis procedures that produced these results can be found in D 1.8.

The detectors composing the triple-stage particle telescopes were selected based on the results of Monte Carlo studies. A set of ion-implanted silicon diodes with thicknesses ranging from 50 μm to 1 mm was purchased to be used as transmission detectors. For the stop detectors, four EJ-204 plastic scintillators of 8 cm diameter and length ranging from 5 cm to 150 cm were already available from earlier experiments with protons up to 150 MeV. An additional cylindrical $CeBr_3$ crystal of 2''×3'' was acquired to stop protons up to 200 MeV.

The scintillators were coupled to Valvo XP2020Q photomultipliers (PMTs). For the silicon diodes, different combinations of charged-sensitive preamplifiers coupled with a fast-filter amplifiers were under consideration with the objective to find the optimal compromise between time and energy resolution.

To test detectors and read-out electronics, an existing vacuum chamber was adapted to accommodate two full telescope arms at 45 degrees from the direction of the incident neutron beam. Detectors and electronics were tested using alpha particles from radioactive sources and proton and alpha beams from the PTB accelerators. These results, which covered energies up to 5 MeV, were extrapolated to the energy range to be covered in the planned experiment on carbon to estimate the expected performances at n_TOF.

The intense γ-flash of the n_TOF neutron source was expected to be the main challenge for the operation of the particle telescopes, in particular of the silicon diodes. In earlier measurements it was found to partially exhaust the dynamic range of the preamplifiers, consequently leading to loss of valid events due to early saturation. To mitigate this, the use of gating circuits inserted between the diode and the preamplifier input, the so-called "switches" [15], was investigated. The purpose of the switches is to drain the charge induced in the detector to ground during the occurrence of the γ flash. After the flash, the preamplifier is reconnected and its full dynamic range can be used for acquiring useful signals.

To test detectors and electronics, in particular the switches, in realistic beam conditions, a Letter of Intent (LOI) [16] was submitted to the Isolde and n_TOF Experiments Committee (INTC) requesting $1{\cdot}10^{18}$ protons on target for test experiments at EAR1. The beamtime was divided in two runs, planned for May 2022 and November 2022 according to the availability of the facility and priority of concurring measurements (as for example the commissioning of the newly installed lead target for neutron production).

3. Detector tests at n_TOF

3.1 First detector test at CERN n_TOF

The objective of the first in-beam detector test in May 2022 was to test the performance of the silicon diodes when paired to switching circuits. The focus of the test was on the stability of the switches, their noise level, and the consequent deterioration of the diodes' energy resolution.
To process the detector signals, standard charge-sensitive preamplifiers (Canberra 2004) combined with fast-filters amplifiers (Ortec 579) were compared to integrated preamplifier-shaper combinations developed for ultra-high rate spectroscopy with diamond detectors (Cividec Cx-L).
The tests at n_TOF lasted five days, from May 9th to May 13th. The vacuum chamber was equipped with two telescopes which were composed of one silicon diode of 50 μm or 60 μm thickness (ΔE_1 detectors), one diode of 500 μm or 1000 μm (ΔE_2 detectors), and either a EJ-204 plastic scintillator of 8 cm diameter and 10 cm length or a $CeBr_3$ scintillator of 5.08 cm diameter and 7.52 cm length (E detectors). The telescopes were placed at 45 degrees from the direction of the incident neutron beam, pointed towards the neutron beam target which was a 1-mm thick sample of either polyethylene or graphite. The samples had a square cross-sectional area of 5 cm × 5 cm, while the beam was collimated to a diameter of less than 2 cm.

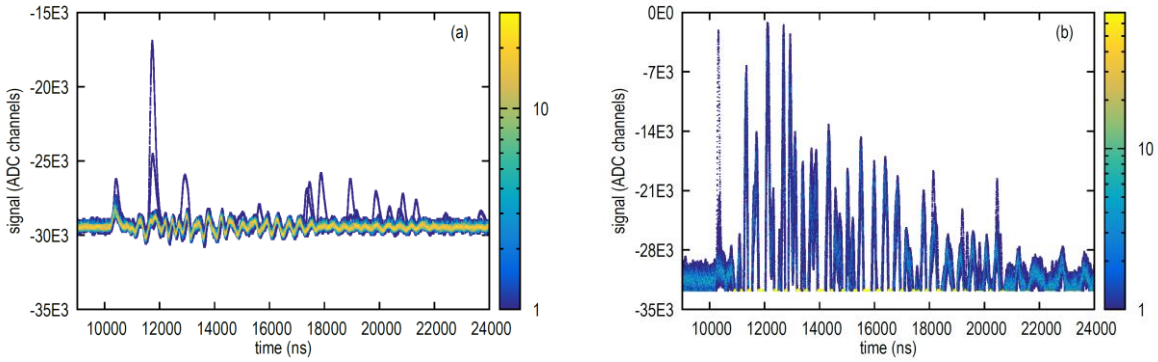

Figure 2: Example of signals produced by silicon diode detectors, recorded during the first test beamtime in May 2022 at CERN-TOF. Panel (a) is for a diode of 51 μm thickness coupled to Cividec Cx-L preamplifier and panel (b) for a diode of 49 μm thickness coupled to a Canberra 2004 preamplifier. The lower part of the oscillations in panel (b), which were much stronger than in the case shown in panel (a), is cut because they were out of range for the data acquisition systems. The signals produced in consecutive beam repetitions after the arrival of the γ-flash (at a time of about 10300 ns) are overlapped to demonstrate how the profile of the ringing noise remains constant.

Figure 2 shows the waveform of the signals acquired with a Micron Semiconductor MSX09 silicon diode of 50 μm thickness coupled to a Cividec Cx-L preamplifier (Figure 2(a)) and one of 49 μm thickness coupled to a Canberra 2004 preamplifier (Figure 2(b)).
The intensity of the γ-flash was found to not pose a problem per se, as it did not cause the saturation of the preamplifiers. However, it was accompanied by electromagnetic noise that produced oscillation in the preamplifier read-out signals with amplitude comparable or higher than the pulse height of valid events. The "ringing noise" was more severe for thin detectors (50 μm and 60 μm thickness) than thick detectors (500 μm and 1000 μm), and for Canberra

preamplifiers more than Cividec preamplifiers, however it could be observed for almost all diode-preamplifier combinations that were tested. This noise appeared at every beam repetition concurrently to the γ-flash and had a duration of about 10 μs. At 185 m from the neutron source, a time-of-flight difference of 10 μm from the γ-flash corresponds to about 1.6 MeV of neutron incident energy, compromising the measurements over the whole range of interest.
The origin of these electromagnetic interferences (EMIs) and their relationship to the γ-flash have not been fully understood yet, however they are under investigation at CERN. The dominant component of the EMI frequency spectrum was roughly estimated from the oscillation period of the read-out signal baseline to range from 2 MHz to 7 MHz. This value was successively confirmed with a dedicated measurements with an antenna [17].
It was observed that the profile of the EMI waveform was constant at every beam repetition, as it also shown in Figure 2. This characteristic had been already exploited in previous experiments to establish an offline data analysis procedure to subtract the ringing from the signals and identify valid events [18]. This analysis is possible also for the silicon diodes as it is also demonstrated in Figure 3.
The data were further analysed to test whether particle identification was possible despite the interferences. The digital waveforms were processed using the Pulse Shape Analysis routine developed at n_TOF [19]. Then, valid events were selected by requiring coincident signals in at least two consecutive detectors, i.e., by identifying the combinations ΔE_1-ΔE_2, ΔE_2-E, or ΔE_1-ΔE_2-E. Finally, the events were sorted into two-dimensional histograms according to the amplitude of the signals, the so-called ΔE_1-ΔE_2 or ΔE_2-E histograms. As the signals' amplitude is proportional to the energy deposited by the particle, these histograms can be used to identify the different particles emitted by the target by applying the ΔE-E technique according to the Bethe-Bloch formula.
In Figure 4, the ΔE_2-E histograms produced by selecting events with time of flight corresponding to incident neutron energies up to 300 MeV are shown before (Figure 4(a)) and after (Figure 4(b)) applying the ringing baseline correction. Despite the low number of counts, it can be noted that this correction results in improved energy resolution and reduction of the noise.

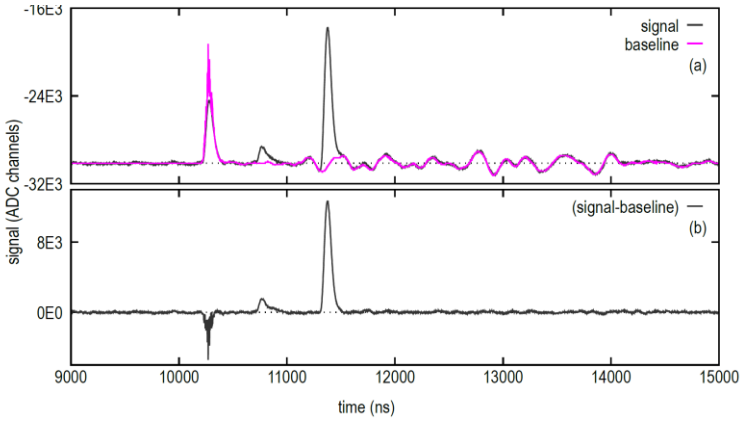

Figure 3: Result of the ringing baseline subtraction procedure applied to the signals of a 507 μm thick silicon diode detector coupled to a Canberra 2004 preamplifier. Panel (a) shows the raw signal, with the γ-flash arriving at ca. 10300 ns, followed by the ringing noise, which is overlapping to the detector signals. Panel (b) shows the result of the baseline subtraction: the γ-flash is suppressed, and the noise under the two signals is strongly reduced. The γ-flash suppression is not an issue as the Pulse Shape Analysis routine determines its arrival time before the baseline subtraction.

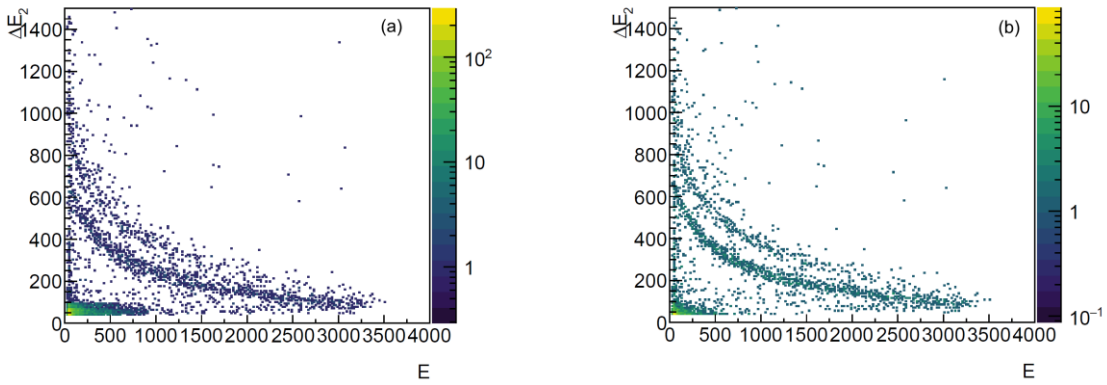

Figure 4: ΔE_2-E histograms obtain before (a) and after (b) applying the ringing baseline subtraction. The scale of the x and y axes is in arbitrary units of signal amplitude. The ΔE_2 detector was a the 507 μm diode coupled with a Canberra 2004 preamplifier. The E detector was an EJ-204 plastic scintillator of 8 cm diameter and 10 cm length. These data were collected using a graphite sample of 1 mm thickness for a beamtime duration corresponding to 5.6×10^{16} protons on target (about half a day). Events with time of flight corresponding to incident neutron energies up to 300 MeV are included. The two "banana-shaped" distributions represent proton and deuteron events.

3.2 Second detector test at CERN n_TOF

As it was found that the γ-flash did not saturate the detectors, the development of the switches was set aside in favour of solutions focused on shielding the electronics from electromagnetic interferences.

To shield the read-out early in the signal chain, the Kapton windows of the vacuum chamber were altered to include an additional aluminium foil of 100 μm thickness. The skin depth of aluminium is 58 μm for signals of 2 MHz and 31 μm for 7 MHz. With a shielding effectiveness of 9 dB times the ratio of the foil thickness to the skin depth [20], the reduction in the EMI picked up in the first stages of the signal chain was thus expected to range from 15 dB to 30 dB. These values were considered as compromise between noise reduction and the introduction of an additional dead layer between the neutron target and the third stage of the telescopes.

The supports of the silicon diodes were redesigned to replace the pin connectors with SMA connectors for a more stable configuration and unshielded cables with shielded cables (see Figure 5).

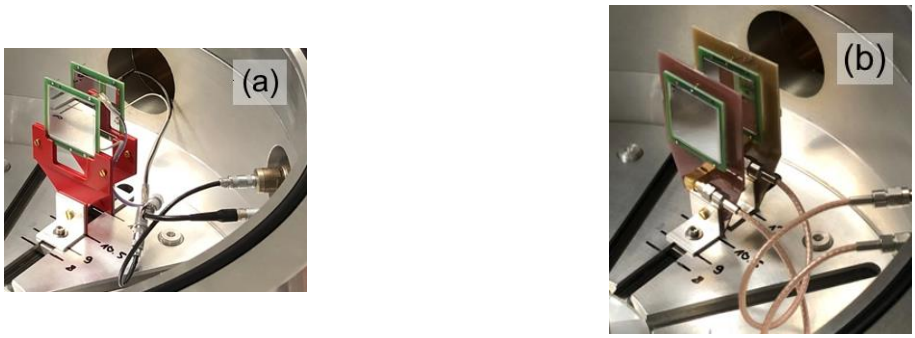

Figure 5: Pictures of the holders and connectors for the silicon diode detectors during the first detector test of May 2022 (a) and the second in November 2022 (b). The pin connectors were replaced with SMA connectors, the cables were shortened and unshielded cables were replaced with shielded cables.

Cremat CR-110 and CR-111 charge sensitive preamplifiers were also purchased to be tested, as they can be operated in vacuum and therefore could be mounted inside the radiofrequency-tight chamber where they should be immune to the ringing noise.
The modified chamber was tested at n_TOF in November 2022, from the 16th to 23rd. Figure 6 shows the reduction of the ringing noise on the detector signals in the case of the CR-100 preamplifier (b), operated in vacuum inside the chamber, as compared to the Canberra preamplifiers (a), operated in air outside of the chamber.

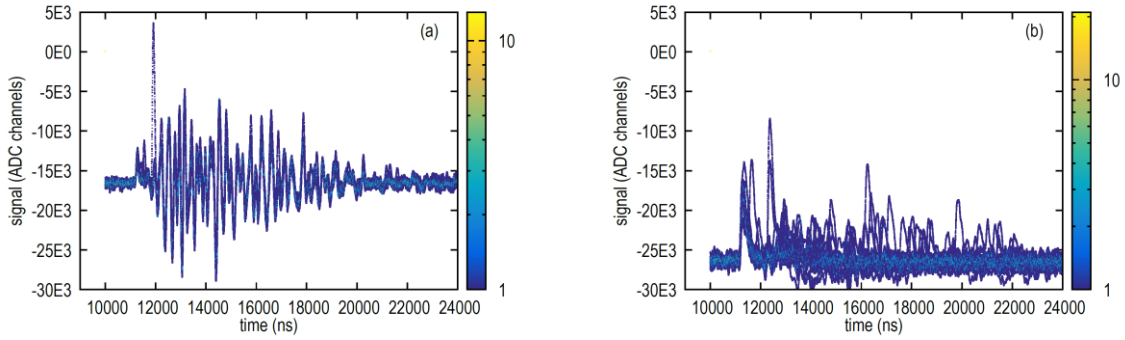

Figure 6: Example of waveforms produced by silicon diode detectors, recorded during the second test beamtime in November 2022 at CERN-TOF. Both panels refer to signals from the same MSX09 detector of 49 μm thickness coupled to (a) a Canberra 2004 preamplifier and (b) a Cremat CR-110 preamplifier. As in Figure 2, the signals produced in consecutive beam repetitions after the arrival of the γ-flash (timestamp at about 11700 ns) were overlapped to form a two-dimensional histogram in time and amplitude in order to facilitate the recognition of the ringing noise. The reduction of the noise from configuration (a) to (b) is mainly the result of being able to mount the CR-110 preamplifier inside the vacuum chamber, which shields it from the EMIs. The Canberra 2004 preamplifiers need to be operated in air to allow heat dissipation.

The data collected in test runs were analysed following the procedure described in the previous section to produce ΔE_1-ΔE_2 and ΔE_2-E histograms. The results collected using a carbon sample of 1 mm thickness as neutron target for a are shown in Figure 7. Particle identification is possible, however the accuracy is limited as the data are affected by significant noise. This could probably be further reduced during the data analysis by implementing all necessary background subtraction procedures, as for example with the subtraction of random coincidences, or measurements with an empty target. It is nevertheless a strong indication that additional effort is still required to select detectors and electronics with low intrinsic noise.

4. Measurement of C(n,cp) DDX

4.1 Beamtime request and count rate estimates

The detector tests demonstrated that the ΔE-E technique can be used to identify light charged particles produced by neutrons with energies at least up to 200 MeV. The limited statistics, however, does not allow to perform a detailed analysis of the energy distribution of the emitted particles. A longer beamtime is necessary to determine the effective limitations of this method. Therefore, in January 2023, a Proposal was submitted to the INTC to request a dedicated beamtime corresponding to 3×10^{18} protons on target [21].

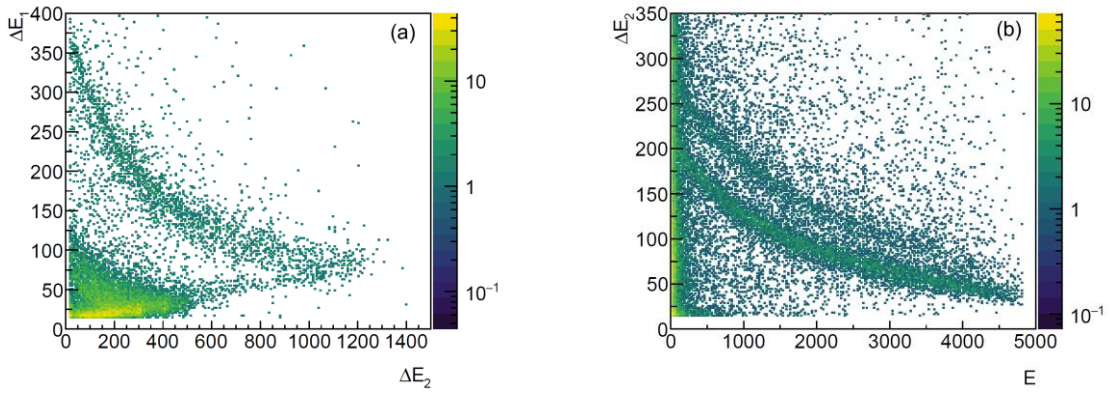

Figure 7: Panel (a) shows the ΔE_1-ΔE_2 histogram and (b) the ΔE_2-E histogram obtained with a 1-mm thick target for an irradiation corresponding to 3.9×10^{17} protons on target, for events corresponding to incident neutron energies from 20 MeV up to 300 MeV. The telescope used for this measurement was composed by one silicon diode detector of 51 µm thickness and one diode of 1043 µm thickness, both coupled to Cividec Cx-L preamplifiers, and an EJ-204 plastic scintillator of 8 cm diameter and 10 cm length.

The expected count rates and the beamtime requirements were calculated using the ICRU DDX data [22] for incident neutron energies below 150 MeV, and the INCL intranuclear cascade model for energies above 150 MeV. In the experimental setup considered for this calculation, the ΔE_2 detectors, which define the telescope's solid angle, were placed at 20 cm from the centre of the graphite sample. This corresponds to an angular acceptance of ±4.3 degrees. Two graphite samples, with thicknesses of 50 µm and 2 mm, were considered. The thick sample was expected to generate most of the statistics, while the thin sample was intended for examining the systematic effects caused by the particle energy loss within the graphite target.

To obtain low statistical uncertainties on the ejectile energy distributions (e.g., below 20% per energy bin), the beamtime request would have exceeded 10^{19} protons on target, which was deemed unreasonable for a proof-of-principle experiment. For this reason, the objective was reassessed to attaining similar statistical uncertainties as those achieved in earlier experiments, at least at the most forward angle of 20 degrees.

Figure 8 shows the expected statistical uncertainty per ejectile energy bin for the emission of protons (Figure 8(a)), deuterons (Figure 8(b)) and alpha particles (Figure 8(c)) produced by neutrons incident on carbon with (100 ± 5) MeV kinetic energy. These results were calculated using the ICRU DDX data, under the assumption of dedicating 25×10^{17} primary protons to the irradiation of the thick sample and 5×10^{17} protons to the thin sample. 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 [23].

With the proposed experiment, the statistical uncertainty on the energy distribution of the emitted hydrogen ions should be comparable to those of existing experimental datasets. The cutoff 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.

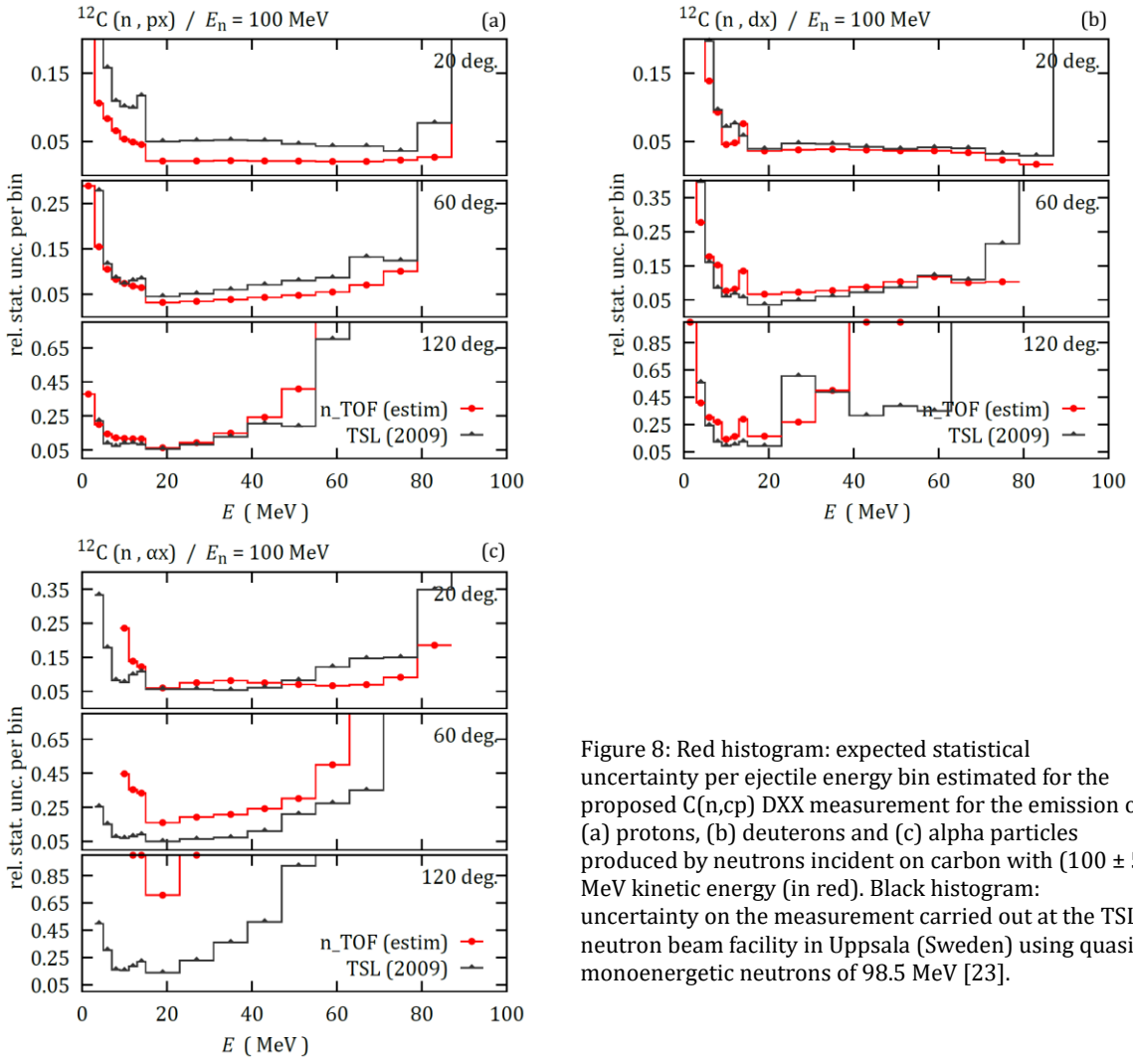

Figure 8: Red histogram: expected statistical uncertainty per ejectile energy bin estimated for the proposed C(n,cp) DXX measurement for the emission of (a) protons, (b) deuterons and (c) alpha particles produced by neutrons incident on carbon with (100 ± 5) MeV kinetic energy (in red). Black histogram: uncertainty on the measurement carried out at the TSL neutron beam facility in Uppsala (Sweden) using quasi-monoenergetic neutrons of 98.5 MeV [23].

4.2 Design and construction of the vacuum chamber for DDX measurements

As briefly mentioned in section 2, the vacuum chamber used for the detector tests was obtained from an existing chamber, adapted to meet the constraints of EAR1 at n_TOF. Its geometry did not match the experimental concept illustrated, for instance, in Figure 1. This test chamber was in fact not intended for the final carbon measurement, but it was rather seen as intermediate tool to determine the required technical specifications. For example, the detector test at n_TOF were crucial to establish that the chamber had to be radiofrequency-tight to shield the first stages of the read-out chain of the transmission detector from the EMI associated with the γ-flash.
The new vacuum chamber was designed and manufactured at PTB by the Department “Scientific Instrumentation”. The technical design of the chamber started in February 2023, with an initial estimate for the delivery of the finished object set to the end of August 2023. The construction, however, was delayed due to an unforeseen staffing shortage. Finally, the vacuum chamber was delivered in November 2023.

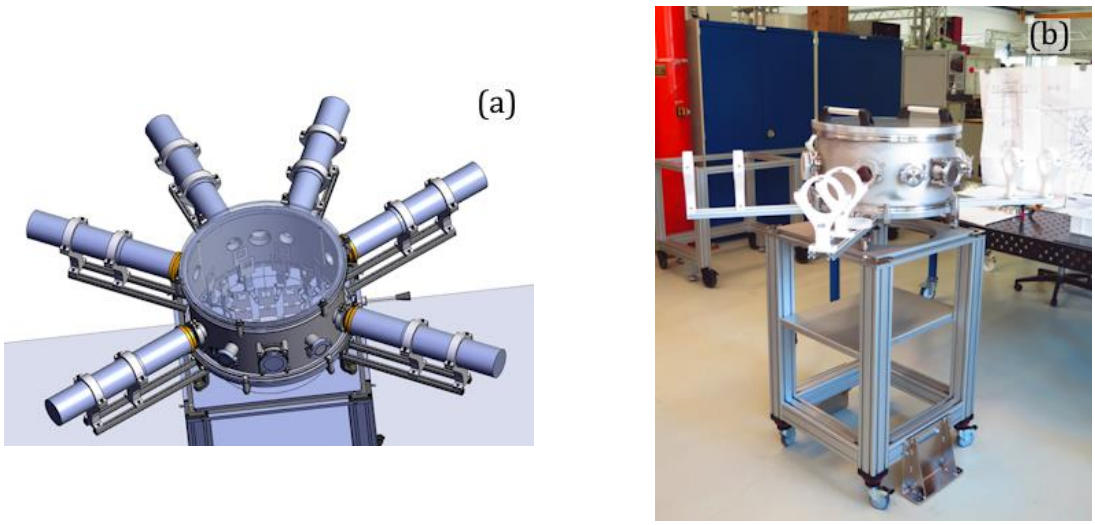

Figure 9: (a) technical drawing and (b) picture of the vacuum chamber for the measurement of double-differential cross sections of neutron-induced light charged particle emission at CERN n_TOF. The technical design and the construction were realised by the PTB Department "Scientific Instrumentation". The chamber can accommodate up to six triple-stage particle telescopes placed at 20 degrees, 60 degrees and 120 degrees with respect to the neutron beam (in panel (a) coming from the top, in panel (b) from the back).

Figures 9(a) and (b) show the technical drawing and a picture of the assembled chamber, respectively. The so-called "DDX chamber" has an internal diameter of 50 cm and can accommodate up to six telescopes arms at the angles of 20, 60 and 120 degrees. The angle between the telescope axis and the neutron beam direction is determined mechanically with an accuracy of 0.1 degrees. The distance of scintillator and centre of the chamber is fixed, while that of the silicon diodes can be adjusted with millimetre-precision. The chamber can also host up to three targets of 10-cm maximum diameter simultaneously. It is possible to select which target is placed at the centre of the chamber without breaking the vacuum, by operating the hydraulic cylinder placed at the side of the chamber.

Kapton windows are used to seal the vacuum and separate the plastic scintillators (the stop detectors) from the silicon diodes (the transmission detectors). The front face of the scintillators is open, while the cylindrical part of the housing is extended to be mechanically and electrically connected to the external flange of the window. By removing the aluminium foils from the chamber windows and the front face of the scintillator's housing, the thickness of the dead layers is reduced, while the extension of the cylindrical part still ensures shielding from electromagnetic noise for the silicon diodes and light tightness for the scintillators. The windows which during an experiment are not coupled with a scintillator are closed using a 2-mm thick aluminium lid. In future iterations, the Kapton windows might be completely removed, and the scintillators might be used as vacuum seals themselves. However, as plastic becomes more fragile in vacuum, this still requires some testing to ensure that this operation mode does not cause any damage.

The height of the cart on which the chamber is mounted is adapted to match the height of the neutron beam in EAR1. Moreover, the position of the chamber can be fine adjusted in the three directions with position screws.

The total weight of the empty chamber is 134 kg; the single components however weight less than 25 kg so that, eventually, they can be manipulated also when working laboratories not equipped with a crane, as it is the case in EAR1.

4.3 Exploratory beamtime

The beamtime request for the C(n,cp) DDX experiment, 3×10^{18} protons on target, corresponds to approximately 30 days of measurement time. This represents a significant commitment of time and resources for both the proposing team and CERN. While preparing for this challenge, the project was also confronted with an unforeseen shortage of human resources. Specifically, the postdoctoral researcher whose position was dedicated to these activities ended their contract earlier than expected (in February 2023), and finding a suitable replacement took longer than anticipated (until May 2024).

The proof-of-principle experiment for the setup for DDX measurements was therefore planned with the aim of providing valuable results while making a prudent use of the available resources; and the objective of the beamtime was thus set to determine the ratio between proton and deuteron production at the emission angle 45 degree.

Several aspects were considered for this decision. Measurements at 45 degrees were already feasible with the existing experimental setup. Monitoring the flux of the incident neutron beam was not necessary for the determination of the ratio, simplifying both the execution and analysis of the measurements. This also allowed the focus to remain on the critical aspects of the experiment which were charged particle detection and identification. The emission rate at forward angle for hydrogen ions is relatively high and precise measurement require a shorter beamtime. It was estimated that only two days of beamtime would suffice to achieve a statistical uncertainty of 4% for the number of emitted protons at a neutron incident energy of (100 ± 5) MeV, and 7% for deuterons. Finally, the ICRU evaluation and the INCL model produce very discrepant results for the production cross sections of deuterons. For example, at 100 MeV of incident energy, the INCL model gives a production cross section of ca 196 mb for protons and 36 mb for deuterons, while the ICRU evaluation reports 182 mb for protons and 85 mb for deuterons. This means that the exploratory measurement could already provide valuable insights into resolving such discrepancy.

The first C(n,cp) measurement took place in September 2023, from the 13th to the 15th. For this, the test vacuum chamber was equipped with two telescopes. The first telescope consisted of a 51 µm thick silicon diode, a 507 µm thick silicon diode, and an EJ-204 plastic scintillator with a diameter of 8 cm and a length of 10 cm. These diodes were connected to Cremat CR-110 charge-sensitive preamplifiers and Cremat CR-200 Gaussian shaping amplifiers. The second telescope included a 49 µm thick silicon diode, a 1043 µm thick silicon diode, and a $CeBr_3$ detector with a diameter of 5.08 cm and a length of 7.62 cm. This setup used Cremat CR-111 preamplifiers and Cremat CR-200 amplifiers. Cremat preamplifiers and amplifiers were chosen because they can operate in a vacuum, allowing them to be mounted inside the chamber to ensure their shielding from γ-flash-induced EMI.

4.4 First results on C(n,cp) and discussion

The data were analysed using the same procedure as in previous tests, with the exception of the ringing baseline subtraction, which was not necessary. Since high-energy protons and deuterons deposit very little energy in the first transmission detector, they were identified using the ΔE_2-E histograms. The events were then sorted according to the time-of-flight measured by the stop detectors, as scintillators provide better time resolution than silicon diodes. The corresponding incident neutron energy was calculated under the assumption that the speed of the outgoing particles matches that of the incident neutron. As the neutron flight path is much longer than

that of the products, this assumption introduces minor deviations from the correct determination, which would ideally require Monte Carlo simulations. Finally, the ratio of proton to deuteron counts was calculated as a function of neutron energy and compared to the ratio of the differential cross section at 45 degrees for proton production relative to deuteron production, as provided by the ICRU evaluation and the INCL model. The results are shown in Figure 10.

In the energy range where the INCL and ICRU data overlap, from 100 MeV to 150 MeV, the difference between their ratios is almost a factor of 3. The experimental data show very good agreement with the ICRU libraries, while the INCL data are not reproduced at all. This discrepancy is not surprising, as the ICRU evaluation was performed using existing neutron and proton data below 100 MeV as a guide, whereas the INCL model was primarily benchmarked with proton data at much higher energies.

The good agreement with the experimental data, despite the preliminary nature of the analysis procedure, seem to suggest that no significant systematic effects have been overlooked. Dead time effects are expected to be small as the count rates are very low, and by performing measurements in coincidence, the background events are also limited. However, caution should still be exercised as the analysis of the systematic effects is still missing. In the energy range from 20 MeV to 30 MeV the experimental ratio is close or equal to zero because the data of the ΔE_1-ΔE_2 detectors, dedicated to the low energy part of the emission spectrum, was not included. Above 200 MeV the results are also not reliable as the identification of high energy protons is not straightforward. According the INCL model, protons emitted at 45 degrees from 200 MeV neutrons can reach energies close to 150 MeV while the EJ-204 plastic scintillator can stop protons only up to 120 MeV. The punch-through protons are still identifiable; however, a detailed analysis is necessary to determine whether their number was underestimated, which could explain the present discrepancy with the INCL prediction.

The experimental data used for preparing Figure 10 can be also found in Annex I. For the reasons listed above, only the results between 30 MeV and 200 MeV are reported for dissemination.

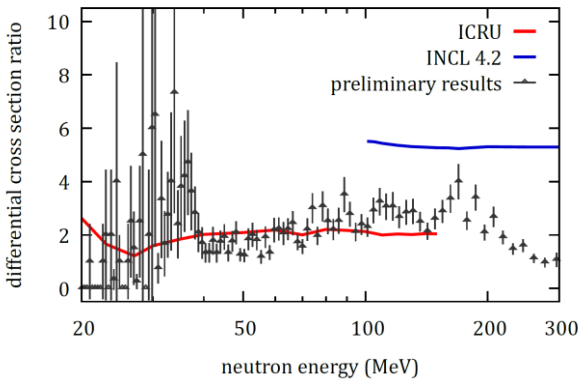

Figure 10: Ratio of the differential cross section for the emission of protons relative to deuterons at an angle of 45 degrees in the laboratory system.The error bars represent the statistical uncertainties. Data from the ICRU evaluation and the INCL model are compared to preliminary results from the test measurements of C(n,cp) at CERN n_TOF. As the analysis of the systematic uncertainties is still missing, these results should be taken with caution, especially below 30 MeV and above 200 MeV.

5. Conclusions

The objective of the current work is to determine whether the measurement of the double-differential cross sections of neutron-induced charged-particle emission using the ΔE-E techniques can be performed at the CERN n_TOF facility to produce data for energies above 100 MeV. Two detector tests and an exploratory experiment on C(n,cp) were performed in 2022 and 2023, and several results are already available.

Measurements at n_TOF in this energy range are severely impacted by γ-flash associated electromagnetic interferences in the frequency range from 2 MHz to 7 MHz. It was found that it is possible to overcome this difficulty with a combination of hardware (shielding of the electronics) and software (subtraction of the ringing baseline in the offline analysis of the signals) solutions. Following these measures, it was possible to operate triple-stage particle telescopes consisting of two silicon diodes as transmission detectors and a plastic scintillator or a $CeBr_3$ detector as stop detector to detect the hydrogen and helium ions produced in neutron-induced reaction up to 200 MeV of incident energy at least.

Preliminary results regarding the emission of protons and deuterons at energies above 30 MeV and up to 200 MeV are presented. At the current state of the data analysis, the experimental data strongly favour the ICRU data over the INCL model in the energy range where the two overlap.

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Annex I

In this table the numerical values of the experimental points presented in Figure 10 are reported. $E_{n,1}$ and $E_{n,2}$ are the lower and upper limit of the incident neutron energy bin, respectively. $R_{p/d}$ is the ratio of proton production to deuteron production at the emission angle 45 degree, obtained as the ratio of proton events over deuteron events detected using the second and third stage of the particle telescopes. u_R is the uncertainty associated to $R_{p/d}$ calculated based on the counting statistics only.

$E_{n,1}$ (MeV)	$E_{n,2}$ (MeV)	$R_{p/d}$	u_R
29.6	30.1	6.00	6.48
30.1	30.6	6.50	4.94
30.6	31.2	0.75	0.57
31.2	31.7	3.33	2.19
31.7	32.3	1.67	1.22
32.3	32.9	2.75	1.61
32.9	33.6	4.00	2.58
33.6	34.2	7.33	4.51
34.2	34.8	2.40	1.28
34.8	35.5	3.80	1.91
35.5	36.2	4.20	2.09
36.2	36.9	4.71	1.96
36.9	37.7	3.63	1.45
37.7	38.4	2.82	0.99
38.4	39.2	2.08	0.73
39.2	40.0	1.69	0.59
40.0	40.9	1.32	0.35
40.9	41.7	1.33	0.36
41.7	42.6	1.78	0.52
42.6	43.5	1.32	0.35
43.5	44.5	1.74	0.42
44.5	45.5	1.92	0.47
45.5	46.5	1.32	0.31
46.5	47.5	1.76	0.38
47.5	48.6	2.09	0.43
48.6	49.7	1.26	0.25
49.7	50.9	1.23	0.24
50.9	52.1	1.84	0.41
52.1	53.4	2.00	0.45
53.4	54.7	1.81	0.38
54.7	56.0	1.18	0.25
56.0	57.4	1.91	0.40
57.4	58.9	1.33	0.27
58.9	60.4	2.18	0.46
60.4	62.0	2.23	0.42
62.0	63.6	2.06	0.42
63.6	65.4	2.21	0.41

$E_{n,1}$ (MeV)	$E_{n,2}$ (MeV)	$R_{p/d}$	u_R
65.3	67.1	2.44	0.44
67.1	69.0	1.73	0.30
69.0	70.9	1.56	0.28
70.9	73.0	2.20	0.42
73.0	75.1	3.00	0.55
75.1	77.3	1.96	0.34
77.3	79.6	3.08	0.56
79.6	82.1	2.51	0.48
82.1	84.6	2.20	0.39
84.6	87.3	2.53	0.48
87.3	90.1	3.51	0.65
90.1	93.1	2.78	0.46
93.1	96.2	2.11	0.35
96.2	99.5	2.39	0.39
99.5	102.9	2.29	0.36
102.9	106.6	2.92	0.48
106.6	110.5	3.25	0.52
110.5	114.6	3.06	0.49
114.6	118.9	3.07	0.53
118.9	123.5	2.67	0.40
123.5	128.4	2.84	0.46
128.4	133.6	2.88	0.47
133.6	139.2	2.49	0.37
139.2	145.1	2.13	0.32
145.1	151.5	2.60	0.39
151.5	158.3	2.89	0.43
158.3	165.6	3.36	0.53
165.6	173.5	4.00	0.66
173.5	182.1	2.53	0.35
182.1	191.3	3.40	0.49
191.3	201.4	2.09	0.30

Annex II

The peer-reviewed paper on this project:

M. Dietz *et al*., EPJ Web of Conferences 288, 01003 (2023),
https://doi.org/10.1051/epjconf/202328801003

attached as Annex II of this report, is published in Open Access as part of the Proceedings of "ANIMMA 2023 – Advancements in Nuclear Instrumentation Measurement Methods and their Applications", that took place in Lucca, Italy, in July 2023.

Detector Development for a Double-Differential Cross Section Experiment with the Emission of Light Charged Particles from High Energy Neutrons

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Abstract— **Double-differential cross section (DDX) data on the neutron-induced emission of light charged particles are required for assessing the risk of secondary tumors in particle radiation therapy. There are only very few DDX data available for discrete neutron energies close to and above 100 MeV for carbon. A measurement of DDX on carbon is planned at continuous neutron energies from 20 MeV to 200 MeV with particle detector telescopes at n_TOF (CERN). Several detector development criteria and challenges are reported such as coincidence timing and electromagnetic oscillations for high neutron energy events with particle separation.**

Keywords **— n_TOF, Double-Differential Cross Section, Carbon, Time-of-Flight, High Neutron Energy, Particle Detector Telescope, Neutron Dosimetry.**

I. Introduction

High-Energy neutrons produced as secondary radiation by cosmic rays or in high-energy accelerators are of importance for radiation protection concerns, radiation treatment planning, and can cause damage in aerospace instrumentation. In particle radiation therapy for cancer, secondary neutrons with energies up to about 200 MeV (proton beams) [1] or 400 MeV (carbon 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], and is important in particular for young patients. The risk assessment requires to calculate the absorbed dose outside the target volume from the neutron fluence. The required kerma factors are calculated from double-differential cross sections (DDX) for the emission of light charged particles, e.g., protons, deuterons, tritons and helium particles.

Experimental DDX data for tissue constituents are still rather scarce for neutron energies above 20 MeV and mostly measured for discrete neutron energies at mono-energetic neutron beam facilities. There are only very few DDX data available for discrete neutron energies close to and above 100 MeV for carbon [5,6,7] and oxygen [8,9]. Discrepancies between experimental data on carbon and data calculated using nuclear models can be observed, e.g., around 100 MeV in most reaction channels, especially for (n,dx) and (n,αx).

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 [10]. 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, a variety of nuclear model calculations [11] must be used.

Therefore, benchmarking and improvement of codes is important in the energy region between 100 MeV and 200 MeV, where not only experimental data are almost completely missing, but also 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 [10].

In summary, this motivates a feasibility study [12] of an experiment of double-differential cross section measurements of carbon with the emission of light-charged particles at high neutron energies between 100 MeV and 200 MeV, which is largely unexplored. In contrast of previous work performed at quasi-monoenergetic neutron sources, a measurement at a pulsed neutron source with broad energy distribution such as n_TOF could provide a continuous coverage of the relevant

neutron energies. With that, new experimental challenges arise and will be discussed in this article.

II. Experimental setup and tests

In this section, an overview of the experimental setup will be given which was used for the detector development phase of the study. Moreover, the neutron facility n_TOF will be presented. Firstly, the detection principle and experimental demands are outlined.

To measure DDX, particle detector telescopes under different angles are needed to identify ejectile species and to determine energy and angle information on the reaction of interest. The telescopes consist of three stages designed to enable particle identification according to their differential energy loss: Two transmission detectors (also referred as "ΔE detectors") and one stop detector (or "E detector"). As a range of light-charged particles from protons to alpha particles is intended to be measured, the first ΔE detector needs to be thin enough that alpha particles of sufficiently low energy can reach the rear detector. The third detector has to be thick enough or made of high Z material to stop the fastest protons. Additionally, a vacuum chamber should be used to minimize the energy loss between ion production and detection, especially in case of the alpha particles. The principle of operation consists in requiring coincident signals for at least two of the three detectors, to identify the particles emitted by the sample in a given direction. The ΔE-E technique is then used to discriminate protons, deuterons, tritons, and alpha particles.

The range of these different ejectiles presents some major challenges for this experiment. Firstly, the incident neutron energy range to be covered extends from several MeV up to targeted 200 MeV or even higher, which requires fast timing of the detectors using the time-of-flight technique. At the same time, a large energy range of emitted particles has to be detected simultaneously, which challenges the particle identification capabilities. Regarding the alpha particles, low detection threshold detectors are needed to avoid missing information of the pulse height distribution. Furthermore, a linear detector response is needed for calibration purposes and for the detection of high-energy protons, where a characterization of the E detector is desired.

The experimental setup at n_TOF consists of two detector telescopes. The transmission detectors are silicon diodes, quadratic in size with an active area of 900 mm², and their thickness ranging from 50 µm to 1000 µm. EJ-204 plastic scintillators of 8 cm diameter and 10 cm or 15 cm length, and a cylindrical $CeBr_3$ scintillator of 3" diameter and 2" length are used as stop detectors. The scintillators are installed outside the chamber, behind thin windows, to allow easy readout of the scintillation detectors using photomultiplier tubes (PMTs). The light-weight aluminium chamber has a diameter of 40 cm and a height of 15 cm, and it is equipped with eight 47-mm diameter flanges with an angular separation of 45 degrees. Four flanges were equipped with windows, of 50 µm Kapton and additional 200 µm or 100 µm aluminium foil respectively, 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 evacuated by a SCROLLVAC pump which produced a residual gas pressure of about 1 Pa to 10 Pa.

A key interest was the readout of the silicon diodes. The resolution of different charge-integrating preamplifiers modules was tested with alpha particles of 5.2 MeV from a ^{239}Pu/^{241}Am/^{244}Cm source at PTB and at n_TOF. Modules like Cividec Cx-L series, Canberra 2004 and Cremat CR110 were used, where the two latter ones were further processed with a fast-filter amplifier Ortec 579. At PTB, the Cividec Cx-L series offered good resolution results for the thicker diodes of about 1% with a fixed signal length in the order of a few hundreds of ns, applicable to time-of-flight experiments. Despite that, the Ortec fast-filter amplification has more flexibility in shaping time, quickly adaptable in respect to the count rate of the studied reaction, but it is worse in terms of resolution by a factor of two to three. Generally, the signals were recorded with the DAQ at n_TOF, which consists of 14-bit flash-ADCs from TELEDYNE SPDevices [13], allowing to record the full pulse shape of each detector signal.

In principle, the neutron time-of-flight facility n_TOF [14] at CERN provides a broad spectrum from thermal up to GeV neutrons, which corresponds to an event time window of about 100 ms for experiments at Experimental Area 1 (EAR1) with a flight path of 185 m, ensuring an excellent neutron energy resolution. The neutrons are produced via spallation reactions of 20 GeV/c proton bunches impinging on a massive lead target. A repetition frequency less than 1 Hz and a high instantaneous rate of about 10^{15} neutrons per bunch lead to a comparable low average fluence of the order of $7*10^4$ cm^{-2} s^{-1} at EAR1, which often defines the amount of beam time required to achieve a given statistical uncertainty.

During the prototype test, data were recorded over about 2.5 days with the detector setup shown in Fig. 1. The sample size inside its holder was 47 mm x 47 mm and a graphite sample of 1.5 mm thickness was used. As shown in Fig. 1. , a polyethylene sample of the same dimension can be exploited as reference sample using the well-defined (n,p) recoil reaction as standard.

A final future experiment will need at least ten times more data to achieve similar counting uncertainties as obtained at monoenergetic sources in earlier work [6]. Nevertheless, many experimental challenges were already observed in this time and their solutions are discussed in the following.

III. Discussion of Experimental Challenges and Results

The main goal of the beam time dedicated to detector development was testing silicon diodes of different thicknesses coupled with different models of preamplifiers, to verify if the energy resolution was sufficient to separate hydrogen isotopes and helium isotopes in the ΔE-E two-dimensional histograms. The interesting part of the spectrum in the MeV range arrives at n_TOF EAR1 in the first ten microseconds after an intense γ-flash which requires fast and stable electronics. This initial γ-flash 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 a loss of valid events due to early saturation.

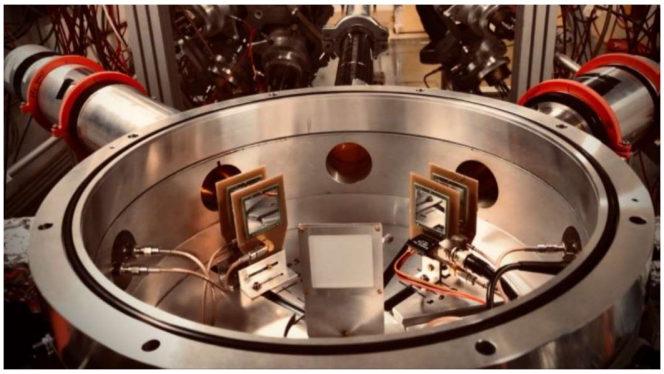

Fig. 1. The picture shows the detectors and a polyethylene sample mounted inside the vacuum chamber used for the detector test, installed in the EAR1 of n_TOF. The vertical axis of the picture (from the bottom to the top) corresponds to the neutron beam direction. The silicon diodes on the left side of the sample are connected to Cividec 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).

A. Experimental Challenges

With the prototype setup, the γ-flash was not the problem in itself, however it did significantly disturb the data acquisition in the first ten microseconds, which corresponds to neutron energies greater than 1.6 MeV. This was found to be associated to electromagnetic noise that produced oscillations in the preamplifier readout signal with amplitudes comparable to the pulse height of light-charged 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 [15].

Several observations were made from the test of different signal amplification configurations. First of all, excellent shielding against electromagnetic interferences is needed early on in the signal chain to avoid distortions of the baseline. Consequently, the scattering chamber, including the Kapton windows, had to be constructed RF-tight using additional Al foils, and the preamplifier modules also needed additional shielding including all cable connections in between, which were already kept as short as possible. Shielded Cividec Cx-L modules performed well outside the chamber, even though small oscillations in the baseline still occurred but were repetitive enough to handle them with a customized baseline subtraction method during the data analysis. Special capacitance-matched preamplifier modules for the thinnest diodes like Ortec 142C or Mesytec MPR-1 were tested and performed worse than the Cividec Cx-L and Cremat CR110 modules. The advantage of the Cremat module was that it can be used inside the vacuum chamber resulting in the best performance with fully suppressed oscillations in the baseline within their random noise level.

B. Status of the Development

The coincidence timing was found to be dependent on the electronic amplification chain and the time difference between ΔE and E detectors was not trivial, as the timing features of the diodes and the scintillator differed significantly. Therefore, the coincidence condition was set rather conservative considering some offset. In a previous experiment [16] using only plastic scintillators for all telescope stages, the identification of coincident events was less difficult because of the higher signal-to-noise ratio.

Two configurations between Cividec Cx-L and Cremat CR110 plus Ortec 579 amplifier on the thin silicon diode are compared in the following as the thinnest diodes were the most sensitive detectors to the challenging experimental conditions at a spallation neutron source.

ΔE_1-ΔE_2 data were produced from a carbon sample using a thin (50 µm) and a thick diode (500 µm or 1000 µm) with the amplification chain outlined in Fig. 1. Due to the short beam time, the data was only analyzed for events covering the full neutron energy range from 5 MeV to 200 MeV. Events with the upper energy limit of 200 MeV were resolved in time-of-flight without distortion from the γ-flash. The data using Cividec Cx-L integrated shaping amplifiers, which had the most promising resolution results at PTB, needed a baseline subtraction procedure at n_TOF which deteriorated the resolution. The results obtained with the Cremat preamplifier inside the vacuum chamber were very promising within the test beam time. Both configurations in this prototype setup delivered good separation between hydrogen and helium ions. Considering the financial aspect and that no special baseline treatment is necessary, the Cremat solution seems favorable for future measurement, where more events will be studied.

C. Future Work

Initial simulation work was performed to study the energy deposition of ejectiles in the detector telescopes. The current resolution is not sufficient to resolve protons, deuterons and tritons, but only hydrogen and helium. Therefore, future tests with different improved Cremat (pre)amplifier solutions and some segmented silicon diodes to reduce their capacitance / noise level are contemplated. Additionally, the effect of the energy loss in the graphite sample on the reconstruction of the energy distribution of the ejectiles will be studied experimentally and by performing Monte Carlo simulations.

IV. Conclusions and Outlook

Detector development of particle telescopes for double-differential cross-section measurement of carbon with the emission of light-charged particles was investigated with shielded preamplifiers and preamplifiers inside the vacuum chamber. Excellent shielding against electromagnetic interferences is clearly needed at a neutron spallation source

like n_TOF and is a key experience from the experiment with the prototype setup.

For two amplification chains, particle identification of hydrogen and helium ions seems possible from the test data, but more work on the resolution of the different isotopes is required. The planning of a future experiment is ongoing to gain sufficient statistics with a well-adapted setup. Finally, this is a new kind of measurement at n_TOF and offers new possibilities of DDX experiments of tissue elements other than carbon with continuous energy coverage in a largely unexplored energy range.

ACKNOWLEDGMENT

We want to acknowledge the workshop and electrical engineers at the PTB department "Neutron Radiation" for their reliable contributions to this prototype setup.

This project has received funding from the European Union's Horizon 2020 research and innovation programme, Euratom research and training programme 2014-2018 under grant agreement No 847552 (SANDA).

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