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 Δ*E*-*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 Δ*E*-*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.

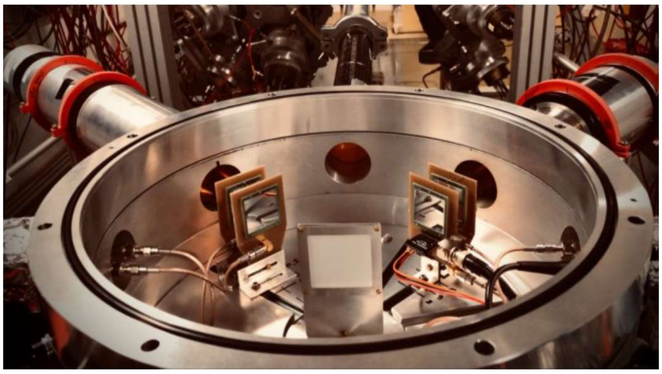

Fig. 1. The picture shows the detectors and a polyethylene sample mounted inside the vacuum chamber used for the detector test, installed in the EAR1 of n_TOF. The vertical axis of the picture (from the bottom to the top) corresponds to the neutron beam direction. The silicon diodes on the left side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