EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of Double-Differential Charged-Particle Emission Cross Sections at n_TOF in the Neutron Energy Range from 20 MeV to 200 MeV

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Abstract

DDX data on the neutron-induced emission of light charged particles are required for assessing the risk of secondary tumors in particle radiation therapy. Previous experiments were only carried out at selected neutron energies using quasi-monoenergetic neutron sources. The n_TOF facility can be used to provide experimental DDX data with continuous neutron energy coverage. Such data would significantly improve the scarce data base for neutron energies close to and above 100 MeV. As first step, test beam time for detector development is requested to extend the existing techniques from the ^{235}U(n,f)/^{1}H(n,n)p experiment to this more demanding task.

Requested protons: $1{\cdot}10^{18}$ protons on target, (split into two runs in 2021 and 2022)
Experimental Area: EAR1

1. Motivation

In particle radiation therapy for cancer, 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 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. The experimental DDX data for tissue constituents are still rather scarce for neutron energies above 20 MeV. Data were only measured for discrete neutron energies and there are only very few DDX data available for discrete neutron energies close to and above 100 MeV for carbon [5-7] and oxygen [8,9]. 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, 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 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 [10].

2. Description of the Project

2.1. Focus and Challenges

The recent experiments for the measurement of the cross section ratio ^{235}U(n,f)/^{1}H(n,n)p at n_TOF EAR1 [12] demonstrated that the neutron-induced emission of light charged particles can be measured up to neutron energies of at least 200 MeV. Therefore, we propose to extend the techniques developed so far to a measurement of DDX data for the neutron-induced emission of light charged particles from carbon. In contrast to the quasi-monoenergetic sources used for the earlier work, a continuous coverage of the relevant neutron energy range could be achieved at the n_TOF facility.

The proposed experiment should focus on the energy range between 100 MeV and 200 MeV which is largely unexplored. The remaining time of the long shutdown of the CERN PS will be used to develop the necessary experimental equipment, i.e. a scattering chamber and detector telescopes suitable for the measurement of hydrogen and helium ions.

The most important challenge for measuring DDX at a spallation neutron source is the intense γ-flash. At n_TOF EAR1 (182 m flight path), neutron energies of 200 MeV and 100 MeV correspond to time separations of about 470 ns and 810 ns from the γ-flash. Detectors must be able to cope with intense signals induced by photons and relativistic particles from the γ-flash and from the related electromagnetic interference. Further challenges are the expected mean event rate which is determined by the moderate 'brillance' of the spallation neutron source compared with typical quasi-monoenergetic neutron sources, the need to use thin samples to achieve low cut-off energies for the detected ejectiles and the small DDX values at larger emission angles. The goal of the project is to achieve statistical uncertainties comparable to those of the two earlier experiments at quasi monoenergetic sources [6, 7].

This project is a contribution to the SANDA project supported under the H2020 framework program of the Commission of the European Union. In the present letter of intent we ask for beam time for testing the required detectors at n_TOF EAR1.

2.2. Expected Performance

The feasibility of the proposed measurement is studied for a prototype set up shown in Fig. 1. It consists of three detector telescopes positioned at emission angles of 20 deg., 60 deg. and 120 deg. The statistical uncertainty is estimated using DDX data and the neutron fluence rate distribution at the EAR1 of the n_TOF facility [13]. The solid angle is defined by the second ΔE detector. The distance of this detector to the carbon sample is 200 mm for the telescope at 20 deg. and 150 mm for the other telescopes. An active area of 400 mm^2 is assumed for this detector which corresponds to the size of commercially available quadratic silicon diodes.

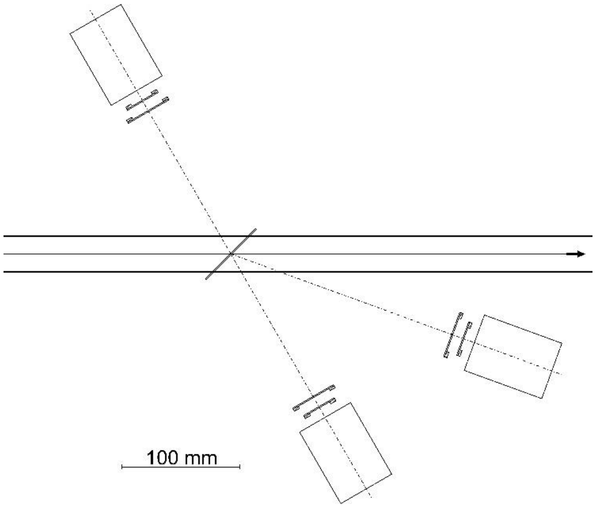

Fig. 1: Set up for the measurement of DDX data at the n_TOF spallation neutron source used to study the feasibility of the experiment. The detector telescopes consist of two thin silicon diodes (50 µm and 1 mm in thickness) and a stop detector mounted in a compact vacuum chamber (not shown on this schematic). The second silicon diode is positioned at 200 mm (20 deg.) and 150 mm (60 deg., 120 deg.) from the carbon sample. Most of the $Z = 2$ particles will be stopped in the second silicon diode while 200 MeV protons can be stopped in the third detector. The active area of the second silicon diode is 20 × 20 mm^2. This detector determines the solid angle of the telescopes. The thickness of the carbon sample is 1 mm. This prototype set up will be optimized and, if possible, extended based on the experience gained during the test experiment.

The identification of the emitted particle species is performed by the ΔE-E method. Fig. 2 shows the expected locations of hydrogen and helium ions in the ΔE_1-ΔE_2 and ΔE_2-E matrices for a telescope consisting of 0.05 mm and 1 mm thick silicon diodes and a 75 mm thick CeBr_3 detector.

For neutron energies below 150 MeV, the ICRU DDX data [11] were used for estimating the number of detected events. They are based on evaluation of experimental data using calculations with the GNASH code [14]. For neutron energies above 150 MeV, DDX data were calculated using MCNPX 2.7 with the INCL intranuclear cascade model. It is assumed that about 3×10^{18} protons are available for neutron production which corresponds to about 30 days of n_TOF operation. This corresponds to the beam time made available for earlier experiments [12].

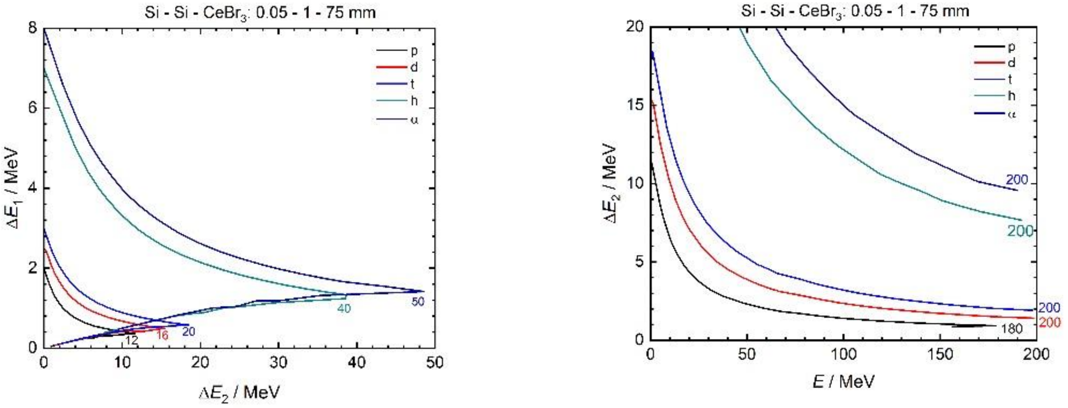

Fig. 2: Identification of hydrogen (p, d, t) and helium ions (h, α) in a telescope consisting of two 0.05 mm and 1 mm thick silicon diodes and a 75 mm thick CeBr$_3$ detector. The colored numbers indicate the initial energy of the respective particle.

As an example, Fig. 3 shows the ICRU DDX data [11] 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 expected relative statistical uncertainty is compared to that reported in EXFOR for the experiment carried out at the TSL neutron beam facility in Uppsala (Sweden) using quasi-monoenergetic 98.5 MeV neutrons. For this comparison, the uncertainties of the TSL data were re-binned to the bin structure of the ICRU DDX data. Similar calculations were carried out for neutron energies of 50 MeV, 150 MeV and 175 MeV. At the latter neutron energy, a comparison with another data set from TSL was possible [7]. Figures for deuteron emission are similar to those shown for proton emission.

The following conclusions can be drawn from these calculations:

- With the proposed prototype experiment, statistical uncertainties comparable to existing data can be achieved at forward angles for the emission of hydrogen ions.
- At backward angles and for helium ions, a better coverage of the solid angle by several telescopes positioned at the same angle or more beam time than that corresponding to 3×10^{18} protons incident of the spallation target would be required.
- The sample thickness of 1 mm effects higher cutoff energies than those achieved at TSL. For helium ions, large corrections would be required for the ‘active’ sample thickness and the distortions of the distribution at low ejectile energies where part of the produced particles cannot escape the sample. The corrections would introduce a significant sensitivity to the uncertainty of stopping power data and could only be avoided by using a second thinner sample and dedicated telescopes for helium ions. This, however, would increase the cost and complexity of the experimental hardware.
- Despite the challenges mentioned above, the suggested prototype experiment will explore the potential of the n_TOF neutron source for a new kind of measurement in an energy range where other neutron sources are not available in Europe. The prototype

experiment should aim at producing competitive data for a few selected angles to provide a reliable basis for a later decision on a more elaborate experiment.

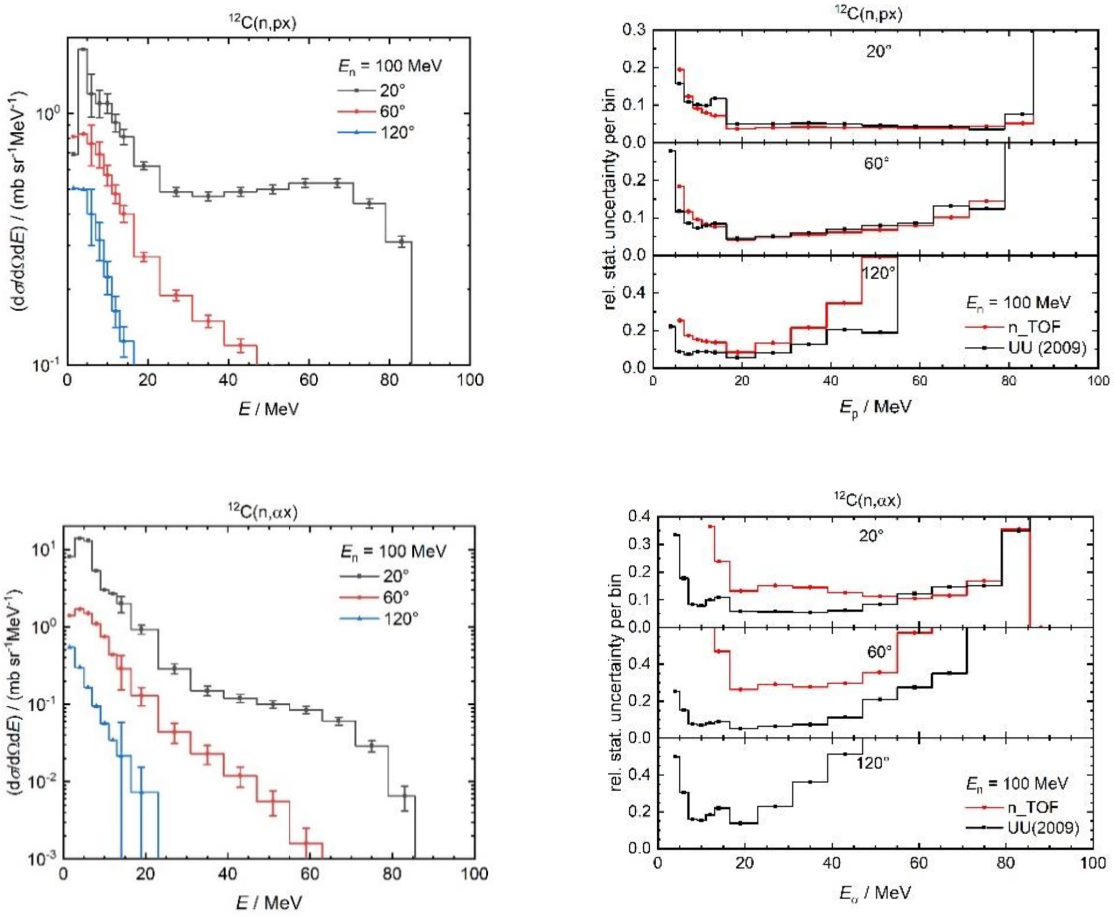

Fig. 3: The left side shows DDX data for p and α emission from ^{12}C and expected statistical uncertainty for 100 MeV neutrons. The cross-section data are taken from Ref. [11]. The error bars indicate the statistical uncertainty per energy bin expected for the proposed experimental setup. Bins with missing error bars indicate particle energies below the cutoff imposed by finite detector thicknesses. The right side presents a comparison with the uncertainty achieved at the TSL facility [6,7], 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. The calculations were made for a 1 mm graphite sample, assuming $3 \cdot 10^{18}$ protons incident on the n_TOF spallation target.

2.3. Test experiment

Compared with the earlier ^{235}U(n,f)/^{1}H(n,n)p experiment [12], the present experiment is more demanding in several respects:

- The energy range of the ejectiles is much larger than those of the recoil protons and low cut off energies must be achieved.
- Helium ions must be detected together with hydrogen ions of much larger energy. Ion species must be separated completely.
- Per ejectile energy interval, the differential emission cross sections are considerably smaller than the n-p scattering cross section. At the same time, the sample thickness is limited by the request for low cutoff energies of alpha particles.

Therefore, as the first step, test beam time is requested to achieve the following objectives:

- Development of more compact detector configurations than in the previous experiment [12] to increase the geometrical acceptance while keeping the unwanted cross talk between detectors within reasonable limits.
- Test of the use of silicon diodes of different thickness to replace the ΔE detectors made from fast plastic scintillators used in the previous experiment. This will improve the energy resolution and the particle identification capability.
- Test of gated charge-sensitive preamplifiers to avoid saturation by signals induced by the γ-flash. This technique was already developed for an earlier experiment using Frisch-grid ionization chambers and will be adapted to silicon detectors.
- Evaluation of the use of $CeBr_3$ detectors to stop energetic protons and deuterons at energies above 150 MeV. Readout using gated PMTs will be necessary to reduce the interference from the γ-flash.
- Optimization and, if possible, extension of the prototype set up shown in Fig. 1, based on the experience gained during the test experiment.

Based on our previous experience with the ^{235}U(n,f)/^{1}H(n,n)p experiment [12] at n_TOF, we suggest splitting the requested $1\cdot10^{18}$ protons for detector tests into two batches. This schedule would allow to react on lessons learnt from the first run and improve detectors before designing the final experiment.

Summary of requested protons:

$1\cdot10^{18}$ protons in two runs

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