EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Characterization of the FOOT neutron detectors for nuclear fragmentation measurements at the n_TOF facility

May 11, 2022

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CERN-INTC-2022-020 / INTC-I-242
11/05/2022

Abstract: We propose a test experiment to characterize several neutron detectors of the FOOT experiment. This would allow their use to study the production of neutrons in nuclear fragmentation processes of interest for hadrontherpy and radiation protection in long-term space missions. The final goal will be to assess the n/γ discrimination capabilities and the neutron detection efficiency of two devices: a liquid scintillator detector (BC-501A) and a BGO crystal operated in Phoswhich mode. These measurements can be carried out in the beam dump of the n_TOF EAR1, without the need of additional proton requests and without interfering with the n_TOF physics program.

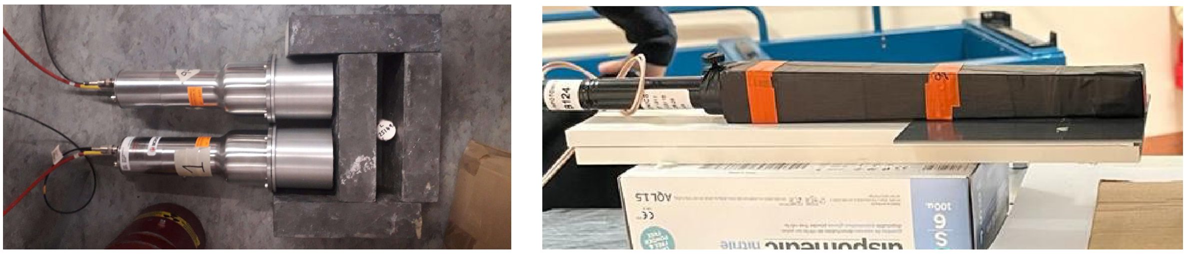
Requested protons: 0 protons on target
Experimental Area: n_TOF EAR1 beam dump

Hadrontherpay is a widely spread technique for the treatment of deep-seated tumors. The main advantage of this approach is the more conformal dose distribution achievable using proton and ion beams with respect to X-rays, which strongly reduces the damage to healthy tissues. However, the contribution of nuclear fragments to dose profiles is still to be accurately evaluated and cross section data relative to fragmentation reactions at therapeutic energies (up to 400 MeV/u) are scarce and limited to few targets and projectiles [1].

The characterization of fragmentation processes is of great interest also for radiation protection in space. In fact, a good knowledge of such reactions is fundamental for the design of new spacecraft shielding and for the correct assessment of radiation risk in long-term space missions, such as travel to Mars [2].

The FOOT (FragmentatiOn Of Target) experiment [3] aims at a full characterization of the nuclear fragmentation reactions of interest in these two research fields. The final goal is to measure the double differential cross section of fragmentation processes in the energy range between 100 and 800 MeV/u and in the diffusion angle. FOOT allows for a precise identification of the produced nuclear fragments through the measurement of their kinematic characteristics. Each detector has been studied to give the best possible resolution with the aim of performing measurements in inverse kinematics and with composite targets. To this purpose, the apparatus has been developed with the capability of accurately characterizing both the primary beam and all the fragments produced in nuclear reactions with the target. The system includes a magnetic spectrometer, a Time-Of-Flight system and a BGO calorimeter.

The setup has been conceived for the detection and characterization of charged fragments. However, one of the most complex issues in hadrontherapy and radiation protection in space is the assessment of the neutron induced damage. To overcome this problem, in 2021, the FOOT collaboration started the development of dedicated neutron detectors that will be added to the current setup in order to retrieve the information on neutron production in the interactions between beam and target. Among the devices currently under study, 2 systems are already available for their use in measurement campaigns. The first detector is a liquid scintillator (BC501-A), sensitive to neutral particles, combined with a plastic scintillator in front, which functions as a veto for charged particles. The active volume of the detector is a cylinder with 3 inches diameter and 3 inches height. The BC501-A has been chosen for its good time resolution and its capability of discriminating neutrons and γ-rays. The n-γ discrimination is a fundamental prerequisite since the main source of background after the removal of charged particles is the one induced by γ-rays. The second device consists of a Phoswich detector based on BGO crystals coupled with fast plastic scintillators in front. The crystals have a truncated pyramid shape, with 2.4x2.4 cm^2 front area, 3.3x3.3 cm^2 rear area and 24 cm length. The BGO Phoswich is being developed as a possible upgrade of the current FOOT calorimeter. In fact, the coupling with a fast plastic scintillator significantly improves the time response of the detector to charged particles, while maintaining a slower rise time on neutron signals. This enables the possibility of performing particle discrimination without the need of an independently read-out veto. Both of these detectors, however, still require a careful evaluation of their neutron detection efficiency, which – in turn - is only possible through their irradiation under well-characterized neutron beams.



(a) (b)

Figure 1: Neutron detectors of the FOOT experiment: (a) BC-501A liquid scintillators and (b) BGO Phoswich.

In this context, the n_TOF facility at CERN is one of the best choices to perform detailed tests on the FOOT neutron detectors. The neutron flux in the experimental areas of n_TOF has been well characterized during the commissioning of last year in the whole energy range through the Time-Of-Flight technique, using 4 different detectors based on different principles and cross sections. The wide energy spectrum (from thermal up to 1 GeV) of the neutron beam available at n_TOF is perfectly suitable to study the response of the detectors to fast neutrons in the energy range of interest for FOOT measurements, between 1 and 800 MeV. In particular, thanks to its long flight path, EAR1 is the most appropriate experimental area to perform measurements on high energy neutrons [4].
We thus propose a measurement campaign in the beam escape line of n_TOF EAR1. The final goal of the measurement is to determine the neutron detection efficiency of the FOOT detectors with an uncertainty attributable to counting statistics at the level of 5%. The measurement will be carried out in different steps. At first, some preliminary tests on the n/γ discrimination capabilities of the detectors will be performed by acquiring data with different radioactive sources, such as ^{88}Y and AmBe. Then, the detectors will be moved to the beam dump of EAR1 to acquire data using the neutron beam. We foresee two different setups:

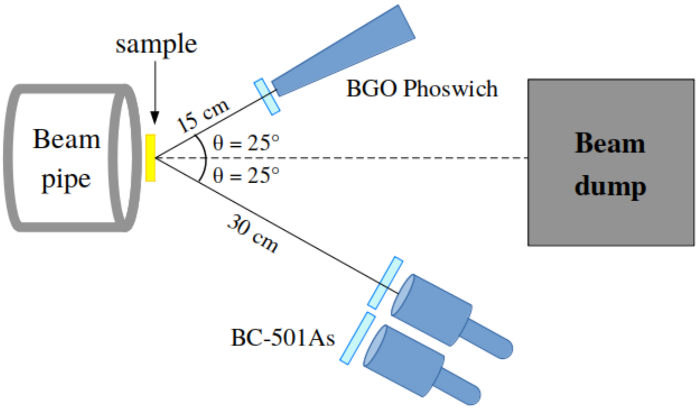


Figure 2: Scheme of the setup for the acquisition with a sample on the beam line.

- Each detector will be placed individually on the neutron beam and the spectrum of detected neutrons can be reconstructed through the TOF technique. In principle, knowing the neutron flux in EAR1, this measurement should be enough to determine the detection efficiency and 1 day of acquisition per device will ensure a statistical uncertainty compatible with our goal. However, the response of these detectors to the γ-flash could prevent the study of high energy neutrons, which is of outmost importance for FOOT measurements.

- To decrease the impact of the γ-flash, both detectors will be placed at an angle θ from the beam line, at a fixed distance from a polyethylene sample (Figure 2). The idea is to exploit the n-p elastic scattering reaction, which is the main reference cross section for high energy neutrons [5–7], in order to detect the scattered neutrons and to measure the neutron detection efficiency. Since the reaction produces an equal number of neutrons and protons, a plastic scintillator veto will also be added in front of each neutron detector to discriminate the signals coming from charged particles. As said before, the BGO Phoswich should already be able to discriminate between charged particles and neutrons. The plastic scintillator veto will be used as a reference to evaluate the identification performances of the BGO.
  Considering the available space in the beam dump of EAR1 and the dimensions of our detectors, we propose to carry out this measurement with the setup shown in Figure 2. One BGO Phoswich and one BC-501A are placed at an angle $\theta = 25°$ with respect to the neutron beam, both pointing at the same sample. The BGO is placed at a 15 cm distance from the sample while the BC-501A distance is fixed at 30 cm. The second BC-501A at larger angle ($\sim 43°$) will be used to validate the results of the main detector. With this setup, the energy E_n of a detected neutron can be calculated as
  $$E_n = E'_n cos^2(\theta) \tag{1}$$
  where E'_n is the energy of the neutron impinging on the polyethylene sample, which can be obtained through the TOF technique, and θ is the angle at which the detector is placed with respect to the beam. The uncertainty on E_n will be mostly determined by the angular uncertainty ($\Delta\theta$) and it will be limited to an upper 9% relative uncertainty. Equation 1 has been obtained ignoring relativistic effects and considering the proton and neutron to have the same mass. Both approximations are reasonable since we expect them to be less relevant than our uncertainties.
  Taking this information into account, the expected number of neutrons per day coming from the n-p elastic scattering on a 5 mm polyethylene sample and impinging on our detectors is reported in Figure 3. Considering an average neutron detection efficiency of 10%, we would reach the required statistics in around 30 days of acquisition. An additional 30 days of acquisition with a 2.5 mm graphite sample has to be taken into account to properly evaluate and subtract the background generated by n-C reactions in the polyethylene.
  An effect that could have an influence on the test is the contribution to background generated by high-energy neutrons scattered in the materials surrounding the detectors. We foresee to add shielding materials (paraffin and/or boron-enriched polyethylene) around the detectors, to reduce it, in case this contribution turns out to be significant.

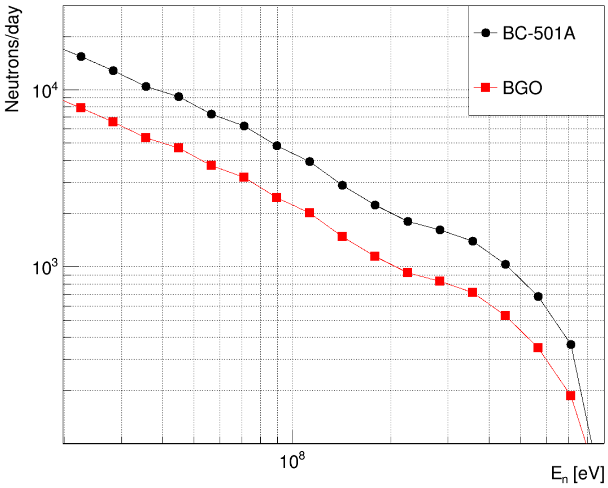


Figure 3: Expected neutrons per day impinging on the BC-501A and BGO detectors for the setup shown in Figure 2 with a 5 mm polyethylene sample. We supposed an average of 10^{17} protons on target per day.

The total time needed to carry out the whole campaign is two months (6×10^{18} protons on target). However, this measurement will be performed in parallel with the experimental activities ongoing in EAR1, which means that **no additional beam request is needed**.

Summary of requested protons: 0 protons on target

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