Study of neutron background at n_TOF facility

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Abstract: To have accurate results when measuring neutron capture cross sections is important a good characterization of neutrons involved in these reactions. In this project, the first steps to compute the neutron background in the two experimental areas at the n_TOF facility at CERN have been performed via Monte Carlo simulations using the FLUKA code. Specifically, the energy spectrum and space distribution for background neutrons within energies between meV and GeV have been computed.

I. INTRODUCTION

Many research fields such as stellar nucleosynthesis, transmutation of radioactive waste, or nuclear medicine, among others, need the study of neutron-induced reaction cross sections. These cross sections are usually measured at neutron beam facilities, designed to cover a wide range of energies (up to 10 orders of magnitude from meV to GeV).

In this case, the n_TOF *(Neutron Time of Flight)* facility [1, 2] was designed and built at CERN to measure the cross section of neutron-induced reactions of many isotopes of interest, for neutron energies ranging from thermal up to 20 GeV. To obtain high precision experimental results it is essential to have an accurate facility characterization in terms of neutron spectra, neutron fluence and flux, among other parameters. This characterization applied to the previously mentioned facility translates to the computation of the neutron background in the experimental area, which are indispensable data to get reliable results.

In the current study, some simulations have been performed in order to characterise the neutron background from neutron beams in the experimental areas. The expected outputs were the energy spectrum of neutrons both in and around the beam and the neutron fluence distribution through beam-transverse regions. This data acquisition has not been made directly in the experimental areas where the neutron background is needed since too much CPU time would have been needed. Instead, a general idea of the neutron background in a different location has been provided to give rise to future more accurate simulations.

II. n_TOF FACILITY AT CERN

The n_TOF facility at CERN [3] uses 20 GeV/c momentum proton pulses given by the Proton Synchrotron (PS) as a neutron source. PS can provide proton intensities up to $7 \cdot 10^{12}$ ppp (protons per pulse), which yields a maximum of $2 \cdot 10^{15}$ neutrons per pulse. The protons given by the PS are launched into a lead target in order to get a neutron beam from it through a spallation process. Right behind the spallation target, a borated water layer can be found so that it captures the thermal neutrons and hence, the 2.2 MeV γ-rays produced by the neutron capture reaction of hydrogen are not generated and a more *pure* neutron pulse is obtained. Taking into account - among others - the tiny pulse time window (7 ns) and the long time between two pulses (from 1.2 s to 16.7 s), a very high energy relative resolution ($7.5 \cdot 10^{-4}$ at 1 keV energies) has been achieved.

As the main aim of n_TOF facility at CERN is to perform cross section measurements, two experimental areas have been implemented. While the experimental area 1 (EAR1) can be found in almost the same direction as the proton beam - just 10° deviated from it (with the aim of avoiding interaction of primary protons with experiments) - and 185 m away from it, experimental area 2 (EAR2) is located 19 m above the spallation target (see Fig. 1). The desired samples to be analyzed are located inside both experimental areas, where several detection systems are placed in order to detect the gamma flashes - used as a start time reference for the time of flight measurement - and other particles coming from the nuclear reactions taking place there.

Between the spallation target and both experimental areas there are several elements such as collimators and magnets in order to remove non-desired particles in the experiments like protons or photons. Furthermore, collimators have the aim of reducing the diameter of the neutron beam so that it becomes smaller than the sample's diameter. In each tunnel there are two collimators and a magnet between them.

The design of the experiment setup (detectors, irradiation samples and space geometry) requires an accurate characterization of the radiation field in the experimental areas. To get these results, simulations have been carried out using the FLUKA code (discussed in the next section). Due to the complexity of the geometry between the spallation target and the experimental areas the simulation time becomes extremely long. Thus, it has to

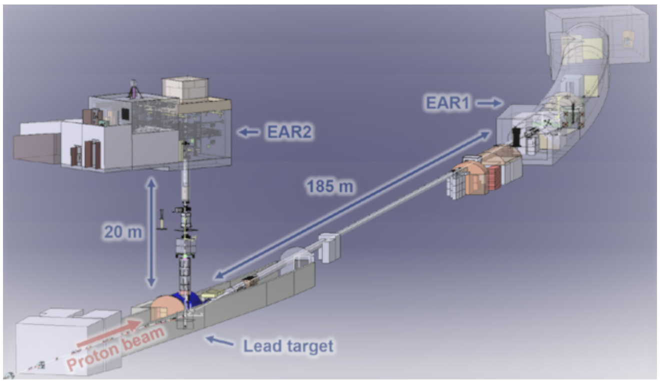

FIG. 1: Scheme of the n_TOF facility including EAR1 and EAR2. Figure taken from [7].

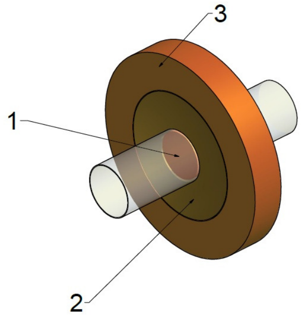

FIG. 2: Detectors implemented with Flair in preEAR2. 1) measures optical neutrons. 2) and 3) measure background neutrons at different distances from the beam.

be divided into shorter steps all over the tubes. This project is focused on the first step transporting neutrons from the lead target to the end of the first collimator in the direction of each experimental area.

III. FLUKA SIMULATIONS

A. Code description

FLUKA [4] is a Monte Carlo particle transport Fortran 77 code used to simulate the transport of particles and their interaction with matter. It can deal with complex geometries thanks to the Flair software [5], a graphical interface for FLUKA. It was created with the aim of easily visualizing the geometry layout, running the simulations, compiling modified routines and even plotting the obtained results from a simulation via *Gnuplot* [6].

B. Input: geometry, source and modifications

The first step to perform neutron simulations in the n_TOF facility is to define the geometry. To do so, an input document previously created with Flair has been used. This document contains all the structure of the facility, the materials used in it, the biasing techniques, the conditions that the user wants to be applied in the simulation, etc.

To make FLUKA detect and apply scoring in different regions where the neutron background is needed, some bodies have been located there to act as a detector. For EAR1, the detection is carried out 138.7 m away from the spallation target, right after the first collimator (here defined as preEAR1). In EAR2, they are placed 10.1 m above the lead target (here defined as preEAR2). Both detectors are made up of two pieces, the first one consists of a cylinder located inside the main tube with the same diameter and it will mostly detect optical neutrons (neutrons in the beam tube that have experimented no interaction). As it is located inside the tube (with vacuum), this piece of the detector is also made up of the same material. The second piece is located around the tube so that it can measure the background neutrons. Thus, it is defined as a cylinder without the inner part (where the vacuum tube can be found) made up of air, the same material as the area where it is located. In preEAR2, due to the larger flux, two detecting rings have been added. While for preEAR1 the ring has a radial width of 16.5 cm, for preEAR2 it is 23.5 cm for each ring. On the other hand, in both areas the longitudinal width is 20 cm. A blueprint of the detectors in this area can be seen in Fig. 2.

The applied source definition in the current study is based on the use of the output of a previous simulation. In that simulation a proton beam was defined in the direction of the lead target and FLUKA transported the proton beam and the resulting neutrons after the spallation process. Scanning disks were located 2.42 and 1.05 m away from the spallation target - both in EAR1 and EAR2 tubes respectively - with the aim of storing information about the particles crossing it. The outputs of this simulation were two files - one for each EAR direction - with 19129982 and 10682565 stored neutrons for EAR1 and EAR2 respectively. Each stored neutron had 10 associated parameters: three coordinates for position (cm), three direction cosines, energy of the particle (GeV), time elapsed (s) from the emission of the proton beam until the detection of the particle, the particle weight (same for all particles) and the FLUKA particle ID (neutrons in this case). In the current study, these files have been used as the neutron source and FLUKA has randomly chosen a neutron and transported it (considered as a primary particle) through all the geometry setup.

Since the relevant information is the number of neutrons per proton pulse and FLUKA is not able to apply this normalization by itself, the desired factor, F_{EAR}, for each experimental area has to be computed manually. To do so, the ratio between the quantity of neutrons stored (n_s) and the primary protons emitted in the first simulation ($p_e = 10^8$) has to be taken. Then, knowing the amount of protons per pulse ($ppp = 7 \cdot 10^{12}$), the factor becomes the product of these two elements, see Eq. (1). For both experimental areas this factor gets values of $F_{EAR1} = 1.339 \cdot 10^{12}\ n/pulse$ and $F_{EAR2} = 4.478 \cdot 10^{11}\ n/pulse$.

$$F_{EAR} = \frac{n_s}{p_e} \cdot ppp\ . \tag{1}$$

IV. RESULTS

In this section we present the results of the simulations performed for both preEAR1 and preEAR2. Every result will be presented for both experimental areas.

First, an analysis of the energy spectrum of optical and background neutrons will prove the huge difference between intensities in both regions. Secondly, the neutron fluence through a beam-transverse region will show the behaviour of the fluence when the distance to the beam axis varies.

A. Energy spectrum

In preEAR1, since the detection has been carried out far away from the lead target, it is difficult to see a relevant difference between optical and background neutrons, as it can be seen in Fig. 3. The optical spectrum is located slightly below the background spectrum. This result is quite interesting because that is exactly the opposite from what one would expect. The reason for this phenomenon is the following.

FLUKA carries out a normalization process when computing the average track length[1] in a specific region. Thus, if the fluence was constant through the whole diameter of both detectors, the spectra should be exactly the same despite their volume difference. The height deviation of both neutron spectra comes from the fact that the detection is being carried out right after having passed through two collimators with different radius. Since they "block" a different percentage of the detector's areas and thus, the effective section changes, the normalization becomes wrong.

In the current case, whereas the effective area[2] of

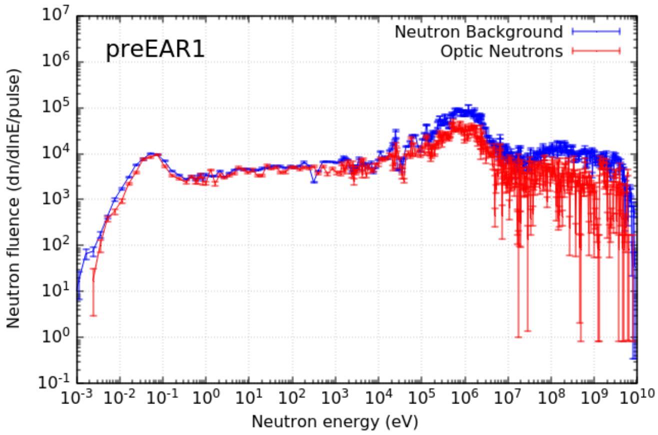

FIG. 3: Energy spectrum of neutrons in isolethargic units at 138.7 m away from the spallation target in preEAR1. Optical and background neutrons are shown.

the optical neutrons detector constitutes 7.57% of it, for the background neutrons detector it is 32.35%. Hence, in case of homogeneous distribution all over the transverse region, the background spectrum should be around 4 times higher than the optical one. As it will be shown in future sections, the distribution is not completely homogeneous. In fact, the optical detector's average track length - considering the effective area for the normalization factor - is twice as high as the background's (seen in Fig. 5). Then, taking into account the fluence and effective area differences, the background spectrum is approximately twice higher than the optical one.

The energy spectrum acquired for preEAR2 is more straightforward (see Fig. 4). Since there is no collimator obstructing the optical neutrons tube, their energy spectrum is located over the background one. Relevant peaks are found in three different energy regions: around 0.1 eV, 1 MeV and 100 MeV; corresponding to thermal, evaporation and spallation regions respectively. A clear correlation between optical and background neutrons can be observed, the background spectrum is shifted about a factor 100 below the optical one throughout all the energy spectrum. The background detector closer to the beam (first ring in Fig. 4) has a small shift in the spallation region, there are more detections there. Since the optical neutrons (the most energetic ones) are less attenuated than those far from the beam, the intensity will decrease the further away from the beam it is measured. Hence, the first ring detector measures more intensity of high energy neutrons than the second ring detector. Table I shows some approximate background fluence values obtained with FLUKA simulations.

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[1] Average track length is defined as the density of particle tracks within a volume bin [cm/cm^3].

[2] The effective area is here understood as the surface of the detector that is non-covered by the collimator. Thus, the neutron density there will be higher.

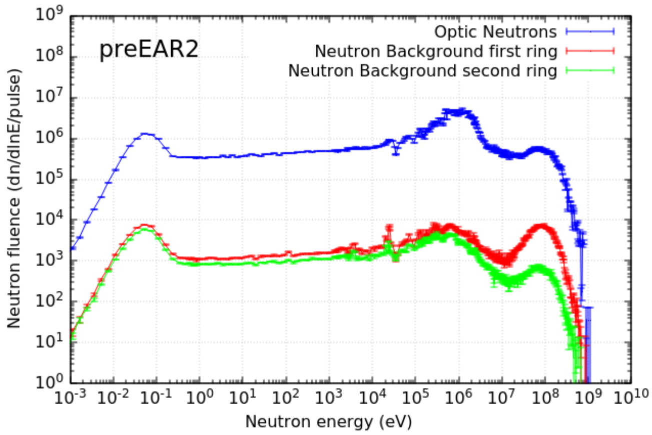

FIG. 4: Energy spectrum of neutrons in isolethargic units at 10.1 m away from the spallation target in preEAR2. Optical and background neutrons are shown.

	Isolethargic Fluence ($\frac{d\phi}{dlogE \cdot pulse}$)	
	preEAR1	preEAR2
Thermal (<300) meV	$(1.01 \pm 0.05) \cdot 10^4$	$(8.1 \pm 0.4) \cdot 10^3$
Isolethargic ($0.01 - 3$) MeV	$(8.5 \pm 0.4) \cdot 10^4$	$(8.3 \pm 0.4) \cdot 10^3$
Spallation ($10 - 300$) MeV	$(1.28 \pm 0.06) \cdot 10^4$	$(7.2 \pm 0.4) \cdot 10^3$

TABLE I: Computed neutron background isolethargic fluence for the detection spots before both experimental areas in three energetic regions. The fluence ϕ is defined in neutrons per cm^2.

B. Neutron fluence

Fluence space distribution has been computed in order to analyze its radial dependence along the tracks from the spallation target to both experimental areas. In preEAR1, as it has already been shown in the spectra analysis, the presence of two collimators makes the fluence space distribution show unexpected values. Although the vacuum tube has a radius of 20 cm, the main neutron beam has just 5.5 cm, the rest of it is blocked by the iron and concrete collimator 70 cm away from the detection region. Since the same collimator is blocking parts of the background neutrons, they are also detected just in the uncovered radii, the region of 25 to 30 cm radius. The upper limit is due to another collimator located 65 m away, in the direction of the spallation target. The fluence space distribution in the center of the tube takes values slightly higher than the background regions, the difference is less than an order of magnitude. This space distribution can schematically be observed in Fig. 5. A more accurate analysis with exact numerical results will be performed later in the current study.

Since the geometry in preEAR2 is more simple, a more expectable space fluence distribution has been obtained. Both the collimator and the main tube have the same radius. Hence, optical neutrons will be the most detected ones. From the center and by increasing the radius, the fluence is reduced by three orders of magnitude, from 10^{-5} to 10^{-8} neutrons per cm^2, per proton (approximately). This space distribution can be observed in Fig. 6. The blue ring around the main tube dividing the optical and background regions appears due to the presence of an iron layer located right in front of the detection regions. Most of the neutrons whose track crosses that region are deviated and therefore the fluence there is smaller.

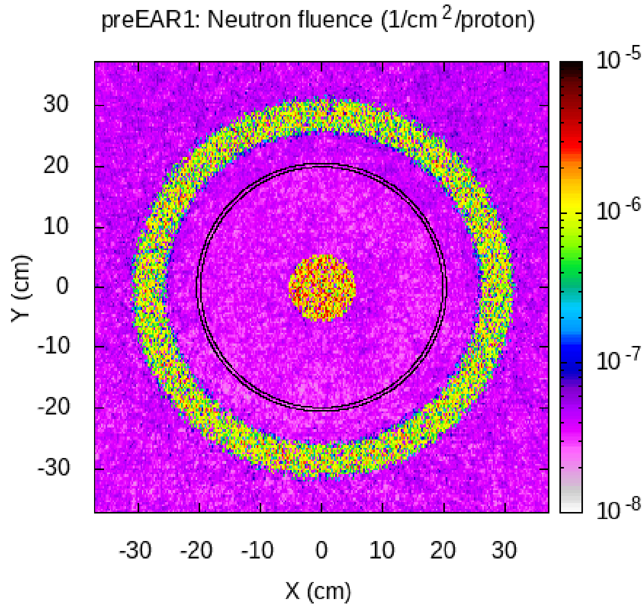

FIG. 5: Neutron fluence space distribution 138.7 m away from the spallation target in preEAR1.

A Fortran code has been created to perform an accurate analysis of the space fluence distribution. Using as input FLUKA's output used to create Fig. 5 and Fig. 6, the program averages the neutron fluence in a ring defined by an inner and outer radius. Repeating this process for 1 mm width rings from 0 to 40 cm radius, a radial distribution is obtained (seen in Fig. 7). Uncertainties for the averaged values are not plotted since they are not perceptible in the given figure - they are all below 5.5%. Exact values are shown in Table II.

V. CONCLUSIONS

In conclusion, it has been proven that the neutron fluence in preEAR2 at a distance of 10.1 m from the lead spallation target is about one order of magnitude greater than the one in preEAR1, at a 138.7 m distance. Further-

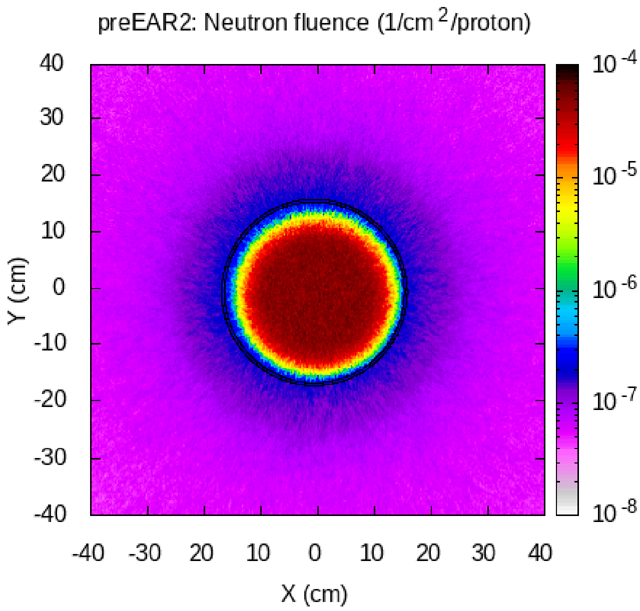

FIG. 6: Neutron fluence space distribution 10.1 m away from the spallation target in preEAR2.

	Radius (cm)	Fluence ($\frac{n}{cm^2 \cdot p}$)
preEAR1	0 - 5.5	$(2.72 \pm 0.02) \cdot 10^{-7}$
	5.5 - 25	$(7.4 \pm 0.5) \cdot 10^{-9}$
	25 - 32	$(1.13 \pm 0.01) \cdot 10^{-7}$
	32 - 40	$(8.0 \pm 0.5) \cdot 10^{-9}$
preEAR2	0 - 16	$(3.282 \pm 0.006) \cdot 10^{-6}$
	16 - 27.5	$(1.44 \pm 0.05) \cdot 10^{-8}$
	27.5 - 40	$(7.4 \pm 0.4) \cdot 10^{-9}$

TABLE II: Average neutron fluence values for different radius ranges. In units definition, n and p stand for neutron and proton respectively.

more, a small difference between the optical and background neutron spectrum in preEAR1 has shown that the collimator gives a higher contribution to the reduction of optical neutrons rather than background. On the other hand, in preEAR2, since the detection has been carried out with no collimator blocking optical neutrons, the deviation between both neutron types in the energy spectrum and the space fluence distribution is more significant. The next step that should be done to carry on with the characterization of the neutron background is to continue with analogous simulations and obtain the results inside EAR1 and EAR2.

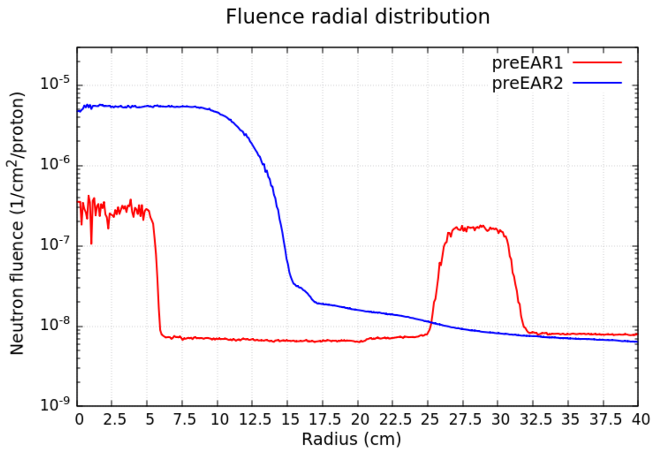

FIG. 7: Plot of radial neutron fluence distribution at preEAR1 and preEAR2.

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