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A low background neutron flux monitor for the n_TOF facility at CERN

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Abstract

A small-mass system has been developed for monitoring the flux of neutrons with energy up to 1 MeV at the new time-of-flight facility at CERN, n_TOF. The monitor is based on a thin Mylar foil with a ^{6}Li deposit, placed in the neutron beam, and an array of silicon detectors, placed outside the beam, for detecting the products of the $^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$ reaction. The small amount of material on the beam ensures a minimal perturbation of the flux and minimizes the background related to scattered neutrons. Moreover, a further reduction of the γ-ray background has been obtained by constructing the scattering chamber hosting the device in carbon fibre. A detailed description of the flux monitor is here

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presented, together with the characteristics of the device, in terms of efficiency, resolution and induced background. The use of the monitor in the measurement of neutron capture cross-sections at n_TOF is discussed.

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Keywords: Neutron flux; Silicon detectors; Carbon fibre; Monte Carlo simulations

1. Introduction

New ideas and developments in the field of nuclear technologies have recently led to a renewed interest in neutron cross-section data. In particular, the design, and eventually the construction, of Accelerator Driven Systems (ADS) for energy production and nuclear waste incineration [1,2], requires new and accurate measurements on a variety of isotopes, many of which radioactive. Needed cross-sections regard capture, fission and inelastic reactions for long-lived fission fragments, minor actinides, isotopes involved in the Th-fuel cycle, and ADS structural materials [3]. On the other hand, high-accuracy neutron capture cross-section data are needed to address some still-open questions in Nuclear Astrophysics [4], as well as in fundamental Nuclear Physics.

The necessity of new and accurate neutron cross-section data for Nuclear Astrophysics and ADS applications have recently led to the construction of an innovative neutron time-of-flight facility at CERN: n_TOF [5]. The main characteristics of n_TOF are the wide energy spectrum of the neutron beam, which extends from thermal energy up to several hundred MeV, the very high instantaneous neutron flux, up to three orders of magnitude larger with respect to previously existing facilities, and the high resolution. The innovative features of n_TOF, and in particular the high flux and low background, are expected to lead to significant improvements in currently available databases, by increasing the accuracy for many isotopes, as well as by providing cross-section data for reactions never measured before.

The accuracy of the neutron cross-section measurement is related, among other factors, to the possibility of monitoring the neutron flux with high precision. In particular, for capture reactions, data concerning the sample under investigation have to be compared to a reference measurement, performed for a sample with well-known cross-sections. In this case, the accurate knowledge of the neutron fluence for relative normalization becomes fundamental. At the same time, any device used for the neutron flux measurement should present a mass as small as possible, in order to minimize the perturbation on the neutron beam and, especially, the background produced by the device itself. At a time-of-flight facility, minimization of all possible background components is of vital importance, since often no other method can be applied for background identification and rejection.

We present here a small-mass system constructed and installed at the n_TOF facility for monitoring the neutron flux. The paper is organized as follows: in Section 2 the principle of operation of the flux monitor is described, together with the simulations performed to optimize its design. A detailed description of the device is given in Section 3, while its performances are discussed in Section 4.

2. The flux monitor design

The accurate determination of neutron cross-sections requires a precise knowledge of the neutron flux and of its energy dependence. In general, cross-sections for any given sample can be determined with respect to a sample with well-known cross-sections, measured in the same experimental conditions. As an example, ^{197}Au, ^{nat}Ag and ^{56}Fe samples can be used as reference for capture cross-section measurements, while ^{235,238}U and ^{209}Bi are typically employed in studies of neutron-induced fission [6]. In principle, it is not necessary to know the absolute value of the neutron fluence impinging on the sample during the measurement, but only a relative normalization factor between the studied sample and a reference one. The value of the relative fluence has to be determined with the required precision, typically of a few percent.

A relative normalization between measurements does not necessarily require the direct measurement of the neutron flux. For the n_TOF neutron beam, produced by spallation of high-energy protons on a Pb target, an accurate normalization between different measurements could in principle be obtained by recording the total number of protons impinging on the target [7]. However, a more reliable monitoring of the neutron flux can be obtained with a device directly mounted in the experimental area, at a relatively small distance from the experimental set-up used for cross-section determination. In this case, particular care has to be devoted to minimize the perturbation caused by the device to the neutron beam and, especially, the induced background. The presence of material in the beam constitutes an important source of background neutrons, which can then directly generate spurious hits in the detectors or undergo further interactions with the material inside the experimental area, with the production of secondary particles, in particular γ-rays. This effect can be particularly important in the measurement of capture reactions, which rely on the detection of γ-rays. At a spallation time-of-flight facility, a reduction of the background can therefore be pursued essentially by minimizing the material present in the beam.

According to these considerations, a small-mass device has been designed for monitoring the n_TOF neutron beam. The device is based on a thin Mylar foil, with a deposit of ^{6}Li (or ^{6}Li compound), inserted in the beam. The well-known cross-section for the ^{6}Li(n,α)t reaction allows to monitor the neutron flux from thermal to approximately 1 MeV energies [6]. The detection of the tritons and α-particles is performed with an array of silicon detectors placed outside the neutron beam, at a small distance from the foil. In this configuration, the background produced by the monitor is related to the interaction of the neutron beam with the Mylar foil and the ^{6}Li deposit, both of which relatively thin. A further minimization of the background induced by scattered neutrons can be achieved by constructing the vacuum chamber hosting the device in carbon fibre.

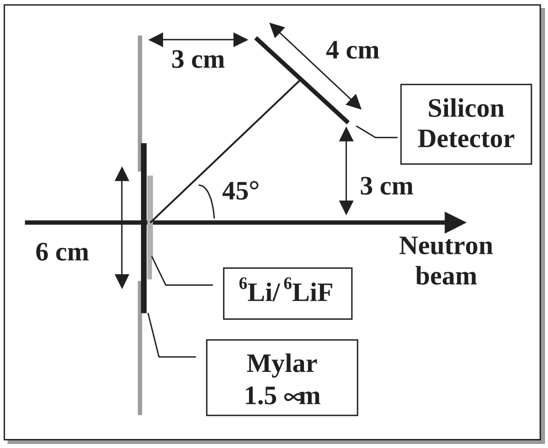

Fig. 1. Schematic view of the Silicon-based flux monitor at n_TOF. A thin Mylar foil with a layer of ^{6}Li or ^{6}Li-compound is inserted in the beam, while an array of silicon detectors is mounted outside the beam.

Fig. 1 shows a schematic view of the neutron flux monitor. Silicon detectors of rectangular shape, with $6\times4\,\mathrm{cm}^2$ area and 300 μm thickness, are placed tangent to a sphere of 4.25 cm of radius and centred around the Mylar foil, at a polar angle of 45° degrees with respect to the beam direction. In this way, a neutron beam of up to 6 cm diameter can cross the flux monitor without touching the edges of the detectors.

The choice of the thickness of the ^{6}Li deposit represents a compromise between the need of a high count-rate and that of a good identification of tritons and α-particles, which is affected by the energy loss within the deposit. The optimal thickness of the ^{6}Li-layer was studied by means of extensive Monte Carlo simulations performed with GEANT-4 [8]. The interactions of neutron at low energy (up to 20 MeV) is simulated for different processes (elastic, capture, etc.), according to the point-wise cross-section data from the ENDF/B-VI library [9]. Because of the recent release of the GEANT-4 package, a check of the validity of the results was performed for some selected cases by comparison with the results

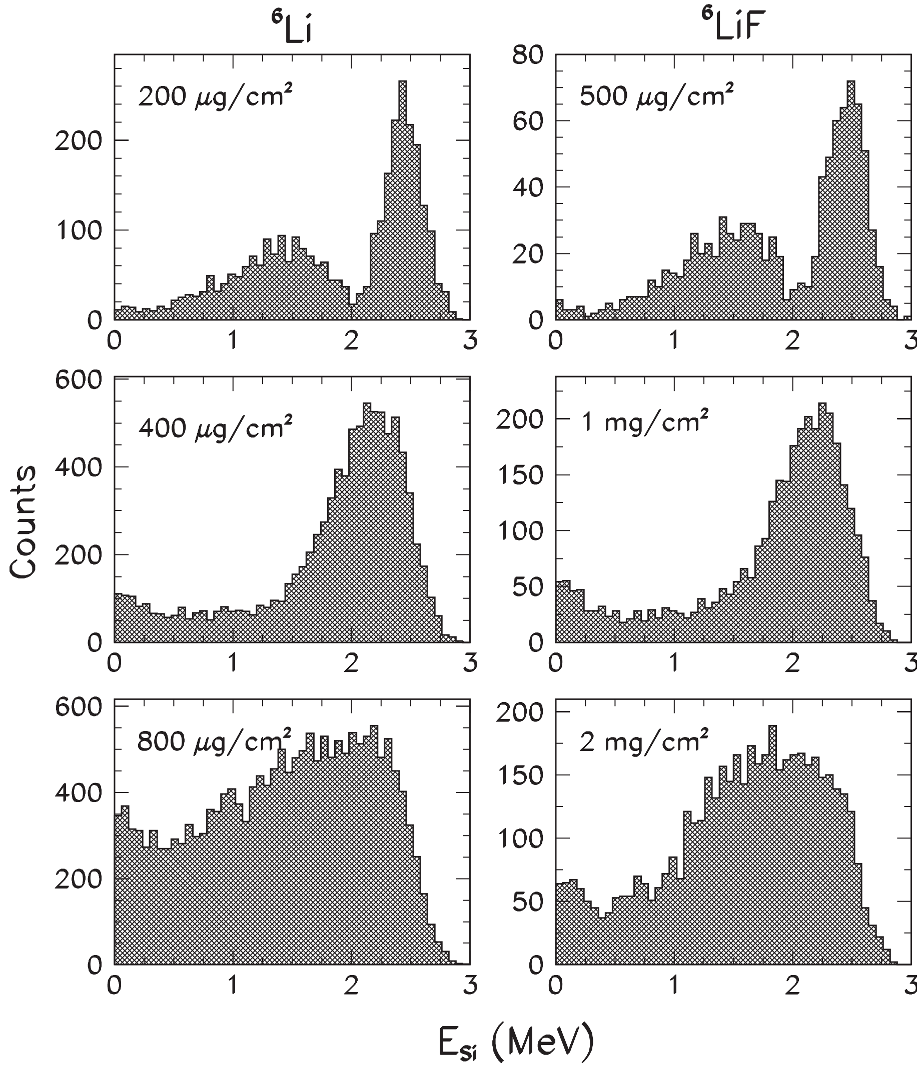

Fig. 2. Simulations of the energy spectrum in the silicon detectors for different thickness of the ^{6}Li and ^{6}LiF deposit. The calculations, performed with GEANT-4, include an energy resolution of 150 keV. The two regions in the spectra correspond to the tritons and α-particles.

obtained with GEANT-3.21 with MICAP interface [10], whose ability to correctly transport low-energy neutrons is well-known [11]. The predicted energy spectrum of tritons and α-particles, the estimated count-rate and the expected background were reproduced by the two codes in a consistent way.

For a realistic prediction of the triton and α-particle spectrum, the energy resolution of the silicon detectors was included in the simulations, using for the noise level a realistic value. The expected energy spectrum for different thickness of the ^{6}Li, calculated assuming an energy resolution of 150 keV, is shown in the left histograms of Fig. 2. Since ^{6}Li is a highly reactive metal and can easily and quickly oxidize when exposed to air, an alternative choice for the deposit may be represented by a ^{6}Li compound, such as ^{6}LiF. The right histograms in Fig. 2 show the results of simulations performed for this material. For very thin

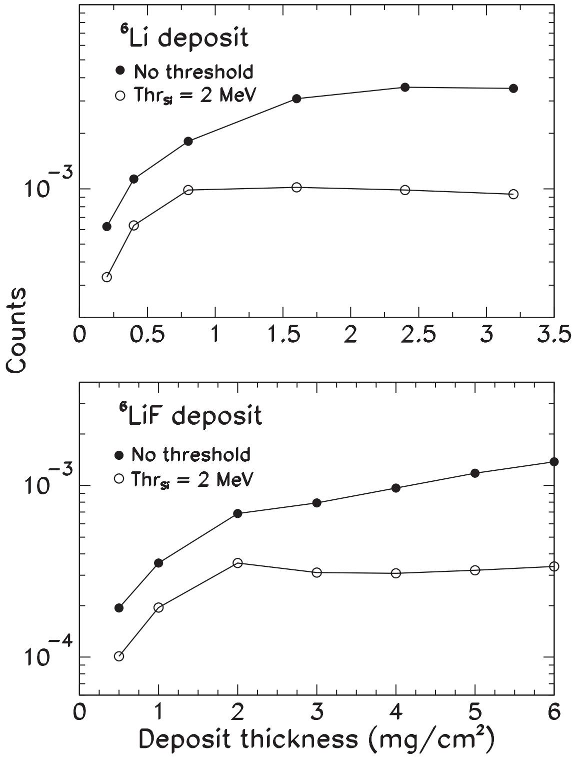

Fig. 3. Simulated efficiency of the Silicon Flux Monitor as a function of the thickness of the ^{6}Li or ^{6}LiF deposit, for 1 eV neutrons. Two cases have been analysed: (1) detection of both tritons and α-particles without any threshold on the deposited energy (solid symbol), (2) detection of tritons only (energy threshold of 2 MeV). The saturation of the efficiency for increasing thickness of the deposit in case (1) is related to the stopping of α-particles inside the ^{6}Li layer, while in case (2) it is due to a larger portion of the spectrum falling below threshold.

deposits, the α-particle and the triton peaks are clearly separated. However, the corresponding charged particle yield is low and may not be sufficient for some specific applications of the device, such as, for example, the precise measurement of the flux in some particular energy regions. As the thickness of the ^{6}Li layer increases, the efficiency improves, but the energy resolution becomes worse, mainly because of the energy loss of the reaction products in the layer itself. Furthermore, for thick layers, some α-particles may be absorbed inside the deposit, leading to a saturation of the efficiency. This effect is evident in Fig. 3, which shows the expected efficiency for neutrons of 1 eV, as a function of the thickness of the ^{6}Li or ^{6}LiF layers. It is important to notice that the saturation occurs for much smaller thickness of the deposit if a threshold of 2 MeV is applied to select only tritons. In this case, the optimal thickness is around 200 μg/cm^2 for ^{6}Li and 500 μg/cm^2 for ^{6}LiF. The results of the simulations indicate that a pure ^{6}Li deposit may be the most convenient, in terms of α/triton separation and efficiency, provided that a protection is assumed to avoid oxidation.

The simulations of the device indicate that the use of a 200 μg/cm^2 pure ^{6}Li layer results in an efficiency of 6×10^{-4} for 1 eV neutrons and 5×10^{-6} at 1 MeV.The overall efficiency for an isolethargic neutron beam in the energy range from 1 eV to 1 MeV is around 4×10^{-5}, which results in a counting rate of ~ 15 events for each neutron bunch (characterized by an area-integrated flux of 4.07×10^5 neutrons with energy between 1 eV and 1 MeV) [12]. At this count-rate, a statistical accuracy of less than 2% is achieved with approximately 200 bunches, a number small compared with the one typically needed in measurements of capture reactions at n_TOF. It should be noted that, for the considered ^{6}Li deposit, the absorption of neutrons from the beam is only 3×10^{-3} at 1 eV, and 2.5×10^{-5} at 1 MeV.

The background induced by the device is essentially related to the interaction of neutrons with the Mylar foil (considering the small value of the elastic cross-section, the deposit of ^{6}Li or ^{6}Li-compound does not contribute significantly to the scattered neutron background). In particular, the hydrogen content in Mylar is responsible for elastically scattered neutrons and for 2.2 MeV γ-rays from the radiative capture. To minimize this background, a Mylar foil as thin as 1.5 μm can be used.

A realistic estimate of the expected background is obtained from simulations performed with a software replica of the device. Fig. 4 shows the number of background γ-rays per neutron, generated by the beam crossing the flux monitor device, in the range between 1 keV and 1 MeV, an energy region of importance in particular for studies of capture cross-sections relevant to Nuclear Astrophysics. Due to the relatively low cross-sections that typically characterize this region, particular

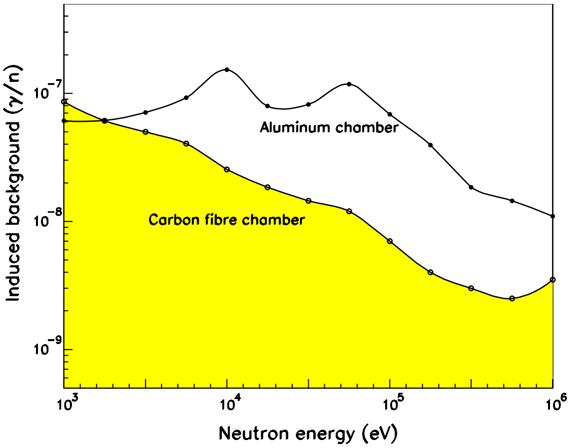

Fig. 4. Background produced by the neutron beam crossing the flux monitor device, for neutrons in the range between 1 keV and 1 MeV. For comparison, the background produced by an equivalent vacuum chamber made of aluminum is shown in the figure.

care has to be taken in minimizing the different sources of background. The results of the simulations indicate that the γ-ray background produced by neutron capture in the Mylar support foil and in the carbon fibre scattering chamber is estremely low. For comparison, the background generated by an equivalent vacuum chamber made of aluminum is also shown in the figure, demonstrating the great advantage of the carbon fibre as structural material.

3. Technical specifications

A small-mass neutron monitor was built according to the considerations reported above. In Fig. 5, some pictures of the apparatus are shown. The Silicon monitor is mounted inside a cylindrical vacuum chamber, with an inner radius of 20 cm, 0.5 cm thickness, and a length of 60.5 cm. At the extremes of the chamber, two standard flanges KF ISO 200 allow to couple the vacuum chamber directly to the n_TOF beam line. The foil with the ^{6}Li deposit and the silicon detectors can be mounted through square flanges built on the cylinder, closed by flat caps held in place by small clamps. A total of five flanges (two small ones for the foil and two large ones for the silicon detectors,

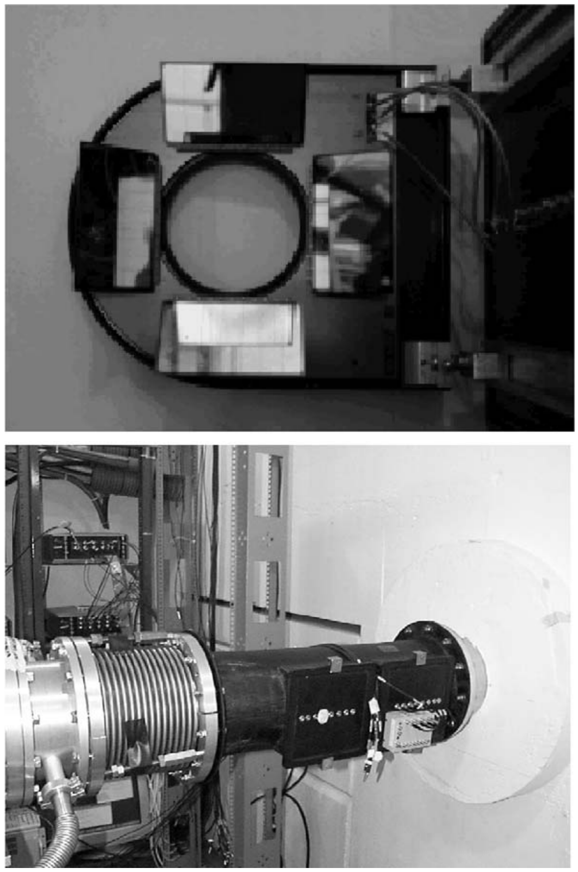

Fig. 5. Pictures of the Silicon Flux Monitor. The vacuum chamber, shown in the lower picture mounted at the entrance of the n_TOF experimental area, is made of two full sectors. Each of the sectors can host the Mylar foil and two arrays of silicon detectors, shown in the upper picture. A third, special sector allows for mounting a detector directly into the beam. All supports are made in carbon fibre.

and one for inserting directly a detector in the neutron beam) allows different monitoring systems to be operated simultaneously inside the scattering chamber, depending on the necessity to maximize the counting rate or to cover different regions of the neutron energy range. The whole device is divided in two sectors, each one equipped with a frame for mounting the foil and two frames for the detectors. All frames are mounted on the caps of the flanges, through rails that allow a precise positioning. The detectors can be positioned in front and on the back of the foil, thus allowing coincidence measurements. The silicon detectors are mounted on a printed copper board, connected to the frame (upper picture in Fig. 5). For each detector, the printed circuit terminates on a LEMO connector mounted on the cap. The lower picture in Fig. 5 shows the whole apparatus mounted at the entrance of the n_TOF experimental area, on the neutron beam line.

All elements of the scattering chamber, i.e. the main cylinder, the two flanges, the ports and the frames for the foil and the detectors, are made in carbon fibre to minimize the background induced by scattered neutrons, given the very low neutron capture cross-section of carbon. The T800H tissue was used for this purpose, glued together with epoxy resin. To optimize the strength of the chamber, and to minimize the employed material, the main body of the chamber was made in one piece only. To improve the shielding of the silicon detectors from the external electronic noise, a copper texture was inserted between two layers of carbon fibre, during the construction of the vacuum chamber.

The final density of the material was estimated to be $1.92\,g/cm^3$. To perform accurate simulations, the exact composition of the carbon fibre was determined by RBS analysis. The following ratio in the number of atoms for the most abundant elements was found: C:O:N:Ca:Br = 2:0.2:0.16:0.012:0.016.

The amount of hydrogen was roughly estimated from that of oxygen and nitrogen, to be approximately 7.5×10^{22} atoms/cm^3 (with an oxygen content of 1.2×10^{22} atoms/cm^3).

The residual pressure required is 1 mbar while the vacuum leakage measured is of $10^{-4}\,mbar \times cm^3/s$, achieved even though large flanges and surfaces are present. The thickness of the chamber was chosen in order to withstand a pressure of 7 bars, a tolerance required by CERN for safety reasons. Compared to the requests for an aluminum structure, the safety tolerance results in a slightly thicker chamber. However, owing to the larger density of the aluminum, but especially to its higher average neutron capture cross-section, the use of carbon fibre results in a reduction of 1/3 in weight and, most importantly, in a strong suppression of the induced background.

A Mylar foil $1.5\,\mu m$ thick is typically used as target of the flux device. A foil with a diameter of 6 cm is appropriate for covering the neutron beam used in capture measurements, characterized by a Gaussian profile with variance $\sigma \approx 0.7$ cm [13]. The ^{6}Li or ^{6}Li-compound is evaporated onto the Mylar foil. If ^{6}LiF is used, no further process is required, since the layer does not oxidize and remains stable when exposed to air. On the contrary, a different procedure has to be followed for a deposit of pure ^{6}Li. The procedure, optimized by the target deposition laboratory of the INFN–Laboratori Nazionali di Legnaro, consists in sandwiching the ^{6}Li layer in between two very thin layers of carbon, to prevent oxidation at the ^{6}Li-air interface or at the Mylar-^{6}Li interface due to the porosity of the Mylar foil. A $10\,\mu g/cm^2$ C layer is sufficient for insulating the ^{6}Li layer from air. First, a deposit of C is made on the Mylar. ^{6}Li is then evaporated on the foil, and on top of it a new deposit of C is made. The stability of such a pure ^{6}Li deposit has been verified over several months of exposure to air.

The choice of the silicon detectors was based on the need of a large area, low capacitance, low dead-layer and ease of operation. The device chosen is a $300\,\mu m$ detectors from Micron Semiconductor, with $6 \times 4\,cm^2$ area. The detector presents a thin Al deposit (200 nm thick), resulting in a small straggling of the low-energy α-particles. The choice of the preamplifiers has to take into account the large capacitance of the detectors and the low deposited energy. Several preamplifiers were tested with the chosen silicon detectors using a three-peak α-source (Am/Th/Pu source). The best signal-to-noise ratio was obtained with the EV 5194 preamplifier, from Evproducts [14], a two-stage hybrid preamplifier, with a sensitivity of 20 mV/MeV, and an input capacitance of 2 pF. The signal from the preamplifier is shaped with a fast filter amplifier, with 200 ns shaping time. Finally, the signals are digitised with the Acqiris Flash ADC [15] of the standard n_TOF DAQ system [16], operated at a sampling rate of 100 MS/s and with 8 Mbytes memory. Typical signals for tritons and α-particles recorded in this way at the n_TOF neutron beam are shown in Fig. 6. A software procedure similar to the one

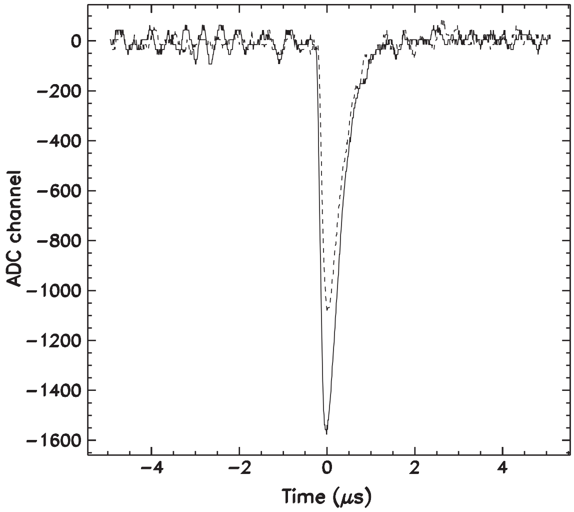

Fig. 6. Typical signals recorded in the silicon detector following neutron interaction inside the ^{6}Li foil. The detector output is acquired by means of a Flash-ADC, operated at a frequency of 100 MS/s. The two signals correspond to an α-particle (dashed line) and a triton (solid line).

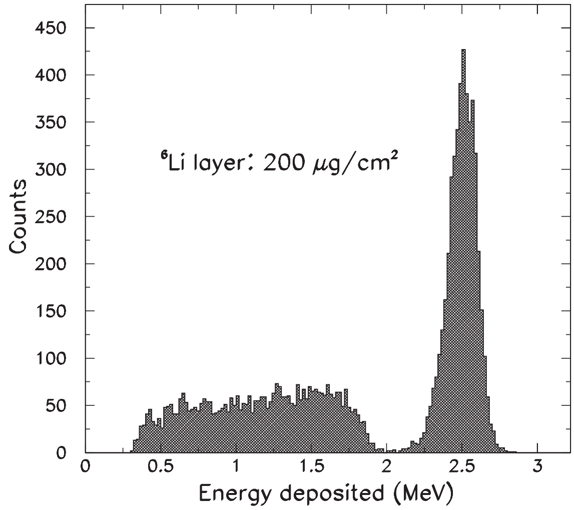

Fig. 7. Energy deposited in the Si detector for a ^{6}Li layer of 200 μg/cm^{2}. The two loci corresponding to tritons (narrow peak at 2.5 MeV) and α-particles (broad spectrum) are clearly separated. For a high accuracy, only tritons are selected in the analysis of the neutron flux.

used for other detectors at n_TOF [16] is applied to the signals to extract the time-of-flight, amplitude, total charge, baseline, and other pertinent information. In particular, the analysis of samples recorded 1024 ns before and after the signal allows to determine the baseline, which is then subtracted from the overall amplitude and charge. The timing information is extracted in a way similar to the operation of a Constant Fraction Discriminator, by determining the time the signal reaches a fixed fraction of its maximum amplitude [16].

The internal electrical layout between the detectors (inside the chamber) and the preamplifier, placed outside, becomes very important to reduce the noise. A good result was obtained by making 50 Ω adapted tracks on a printed circuit to transfer the signal from the detectors to the flange, on which the preamplifiers are connected.

4. Performance of the device

The flux monitor has been mounted and operated at the n_TOF facility. A foil with a deposit of 200 μg/cm^{2} of pure ^{6}Li, sandwiched between two layers of 10 μg/cm^{2} of carbon, was employed in the first measurements. A typical hardware threshold of 100 keV is applied during the measurement, to suppress electronic noise.

Fig. 7 shows a spectrum of the energy deposited in the silicon detectors. As expected, the regions corresponding to the tritons and α-particles are clearly separated. The peak centered at 2.5 MeV corresponds to tritons, which loose only a minimal fraction of their energy inside the ^{6}Li deposit. On the contrary, due to their larger energy loss, α-particles show a broader spectrum reflecting the uniform distribution of the production depth inside the ^{6}Li layer. It should be noted that part of this spectrum, corresponding to the lowest energy α-particles, falls below the threshold used on the Flash ADC, determining a loss of efficiency. Although this can be estimated from the simulations, more accurate results are obtained by analysing the triton signals only.

To extract the energy-dependent neutrons flux from the silicon detectors, a correction for the ^{6}Li$(n,\alpha)^{3}$H cross-section and for the geometric efficiency of the apparatus has to be applied. A comparison of different databases of evaluated cross-sections shows that all of them agree within

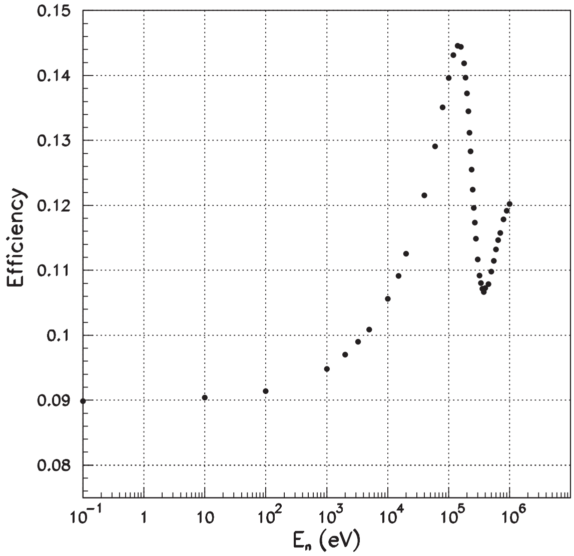

Fig. 8. Efficiency of the Silicon Flux Monitor for the detection of tritons emitted in the ^{6}Li(n,α)3H reaction. The increase in the 10–100 keV region is related to the forward-peaked angular distribution.

2% up to 100 keV. At higher energy, the determination of the flux is affected by a larger uncertainty in the evaluated cross-sections. Nevertheless, a monitoring of the neutron beam can still be performed up to 1 MeV, since only the relative value between different runs is required.

The geometric efficiency was estimated by means of the Monte Carlo simulations, performed with the code GEANT-4, as described in the previous paragraph. The exact geometry of the foil and of the silicon detectors was implemented in the code, as well as the neutron beam profile [13]. The emission of tritons in the code is assumed isotropic in the centre of mass system. As reported in literature [17], this assumption holds valid only up to approximately 1 keV. Therefore no correction for the angular distribution was applied to the estimated efficiency up to that energy. The extracted value is approximately 9% for a configuration with four silicon detectors.

Above 1 keV, tritons are preferentially emitted in the forward direction in the centre-of-mass system. The angular distribution of tritons for different neutron energies, extracted from the ENDF-B/VI database [9], has to be taken into account in the simulations of the efficiency at higher neutron energies. Since this is not included in the code GEANT-4, a specific routine was added so that, for each event, the emission angle of the triton was simulated according to the interpolated distribution at the corresponding neutron energy. The overall efficiency of the flux monitor to tritons is shown in Fig. 8.

5. Summary

A small-mass neutron flux detector has been set-up to monitor the neutron beam at the new n_TOF facility at CERN. The main features of the device are the minimal perturbation of the beam and the very low-induced background. These characteristics have been achieved by inserting in the neutron beam only a thin Mylar foil with a ^{6}Li (or a ^{6}Li-compound) layer. An array of silicon detectors, used for recording the charged products of the ^{6}Li(n,α)^{3}H reaction, is placed outside the beam around the foil. In a set-up with four detectors, a geometric efficiency slightly below 10% is achieved, if only tritons are analysed. To host the device, a modular carbon-fibre scattering chamber has been built with the aim of minimizing the background induced by the interaction of scattered neutrons. The chamber allows several monitoring sectors to be operated simultaneously. A particular procedure has been used to evaporate on the Mylar foil a pure ^{6}Li deposit that remains stable even when exposed to air for several weeks.

The flux monitor here described has been mounted inside the n_TOF experimental area, at 182 m from the spallation target, and is operated in measurements of capture reaction cross-sections. The results of dedicated measurements of the neutron flux, used also to validate the response of the monitor against a calibrated neutron detector [18,19], will be the subject of a forthcoming publication.

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