EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — SL DIVISION

CERN SL-2002-010 (ECT)

Radioprotection and shielding aspects of the nTOF spallation source

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Abstract

The neutron Time of Flight (nTOF) facility at CERN is a high flux neutron source obtained by the spallation of 20 GeV/c protons onto a solid lead target. The first experimental measurements performed in Apr. 2001 have revealed an important neutron background, 50 to 100 times higher than expected, along with some secondary effects like air activation, with a strong presence of ^{7}Be and ^{41}Ar. In a subsequent study this neutron background was accounted to the strong presence of charged particles and especially negative muons, resulting from the interaction of the high-energy proton beam with the lead target. The present paper reports the study and solutions to the radioprotection and shielding aspects related to the nTOF spallation source.

Presented at the SATIF-6 2002 (Shielding aspects of Accelerators, Targets and Irradiation Facilities
Stanford, April 10-12 2002

Geneva, Switzerland
May 2002

Introduction

The neutron Time of Flight (nTOF)[1,2] facility at CERN is a high flux neutron source obtained by the spallation of 20 GeV/c protons onto a solid lead target. The proton beam is delivered by the CERN Proton Synchrotron[3], capable of providing up to four sharp bunches (6 ns) with an intensity of 7×10^{12} protons per bunch, within a 14.4 s super cycle. The new facility is operational and has been commissioned in Nov. 2000 and Apr. 2001 with the main goal to check the conformity of its characteristics. Part of the commissioning program was dedicated to measurements on the safety of the installation. During the measurements performed up to the end of June 2001, a high background was observed[4], roughly two orders of magnitude higher than the one expected. This background was later related to neutrons generated by the negative muons capture on the material near the experimental area, and the appropriate actions have been taken. The present paper describes the study and solutions to the background problem, along with radioprotection and shielding aspects related to the nTOF spallation source, with emphasis on the conditions needed for neutron induced cross section measurements.

The Lead spallation target

The major part in the design phase of the nTOF facility was focused on the lead spallation target. The target is made with pure lead blocks and its shape is 80 × 80 × 60 cm^3, except for the spallation area where a volume of 30 × 55 × 20 cm^3 was removed to have the nominal design dimension[5] (fig. 1). The target is mounted on a steel support and is submerged in water contained in an aluminum alloy vessel. The water layer surrounding the lead block is 3 cm thick except at the exit face of the target where it is 5 cm thick. The walls of the aluminum container are 0.5 cm thick, except the exit wall that consists of a thin single metallic aluminum window[5] of 1.6 mm thickness, 80 cm diameter. During operation the maximum dose recorded by the Safety Division (TIS) detectors was of the order of 10 Sv/h in the target area. The target was removed at the end of the first commissioning period (14 Feb. 2001) for inspection. After exposing the lead target to 2_10^{16} protons of 20 GeV/c and 2 months of cooling the maximum dose record was 1.1 mSv/h at the hotspot and an average of 400 μSv/h was measured in the front face of the target. The measurements are compatible with the simulations[6] reporting a maximum dose of ~ 2 mSv/h at the hotspot. The aluminum container had an dose of 5 μSv/h and 15 μSv/h was measured on the inox screws.

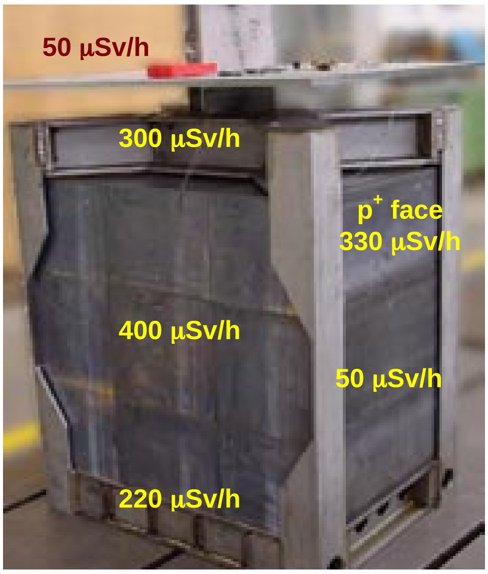

Figure 1. Activity of the spallation lead target after 2 months of cooling.

The total volume of water used in the cooling system is about 700 l; 20% of it remains in the aluminum container. We can reasonably assume that the specific dose of the whole water volume is five times lower than the specific activity in the water inside the container, as this water permanently circulates in the cooling system. After one day of decay, the activity is mainly due to ^{7}Be and tritium, with 53.3 d and 12.33 y half-lives respectively. For an irradiation of 3×10^{15} protons on the lead target and 1 day cooling the simulations[6] gave a tritium level of 700 Bq/l and 20000 Bq/l from ^{7}Be. The measurements showed 600 Bq/l for the tritium and the 30 Bq/l for the ^{7}Be. The difference in the ^{7}Be shows the effectiveness of the resins filter. The water was contaminated also by other isotopes, namely: ^{51}Cr originating from the canalization, ^{122}Sb, $^{198,200\text{-}202}$Tl and ^{200,202,202m,203}Pb coming from the lead target.

Thermodynamic behavior of the lead target

The energy deposited by the proton beam in the lead target induces a temperature increase. Thus, the temperature behavior of the target has been monitored by means of six thermocouples inserted in different positions in the lead block. At proton intensities of $\leq 10^{12}$ protons/pulse no visible structure in the temperature behavior could be observed. For the highest proton intensities of $7\text{x}10^{12}$ protons/pulse a clear temperature rise was observed. However, the maximum temperature remained below 70^{o}C, in agreement with the calculations[7].

Sound waves

At proton intensities above $3\text{x}10^{12}$ protons/pulse a clear acoustic signal could be perceived coming from the target region. The signal was audible even behind 10 m of concrete shielding. The energy deposited in the centre of the target is mainly converted to heat almost instantaneously. Due to the large mass-inertia and the short time a pressure is created and the equilibrium inside the material is disturbed. The potential energy is converted into kinetic energy, which creates elastic vibrations resulting in a sound wave traveling through the material. These elastic vibrations travel through the target and only ~15% goes into the water. Analytical calculations[7] showed a maximum displacement of the lead target of a few μm and a maximum pressure at the hotspot of 7 bar. The calculations indicate that the appearing forces are such that possible damages to the window, the welds of the water tank and other structures can be excluded. Recent studies[8] have shown that a displacement if 1 $\mu m/m^2$ can produce up to 75 dB noise. Several detectors have been mounted on the lead target to measure the effect: accelerometers, strain gauges, and crack detection gauges.

The Background in the Experimental Area

During the measurements performed up to the end of June 2001, a significant background (fig.2) was observed[4], roughly two orders of magnitude higher than expected. This background has consequences on capture measurements both in terms of accuracy and required beam time. The background was visible with various detectors: liquid scintillators C_6D_6, TLD-7, Bicron 702, CR-39 track edge detectors. However, it was not possible to identify the mechanism responsible for producing it. The most important characteristics were the strong left-right asymmetry (with respect to the beam line), the intense prompt flash appearing outside the beam line and the long time component up to few ms. In order to understand the origin of this background, several scenarios have been proposed, such as fast neutrons coming directly from the target area, muon interactions, the collimation system, imperfections in the shielding, the neutron escape line, etc.. We have demonstrated that the most likely explanation of the neutron background in the nTOF experimental zone is negative muon captures occurring in the walls and materials of the experimental hall.

Neutron generation by muons is a process that has been known for a long time[9], which is particularly important in those situations like underground sites or atmospheric showers at ground level where muons are known to dominate the radiation environment. Actually, muons can produce hadronic interactions through two different mechanisms:

- Photo-nuclear interactions via virtual photons
- Negative muon capture with μ^- brought to rest through the weak process:

$$\mu^- + {}^A_Z X \rightarrow \nu_\mu + {}^{A}_{Z-1}Y^*$$

The former process involves muons of (relatively) high energy and has a mean free path of a few hundred meters in earth. Thus, it is not supposed to contribute significantly in the nTOF. The assumptions used in our simulation models predict that ~50% of μ^- stopping in concrete undergoes nuclear capture. Experimental spectra of neutrons emitted following μ^- captures show an evaporation peak consistent for multiplicity and excitation with single nucleon excitation, plus a low intensity tail extending up to several tens of MeV which cannot be explained without resorting to more complex interactions. The model embedded into FLUKA[10] uses a combination of single and two-nucleon absorption within a cascade pre-equilibrium evaporation model, with the relative importance of the two components set in such a way to get a satisfactory description of the experimental data.

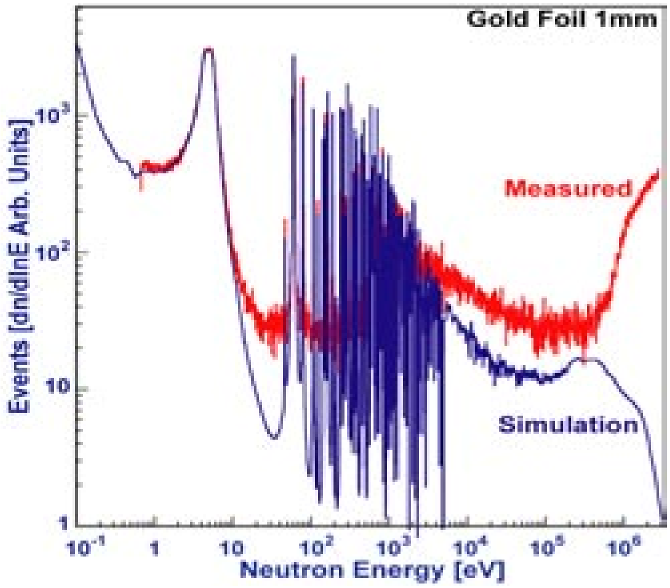

Figure 2. Experimental spectrum from 1 mm thick gold sample compared to the expected effect constructed from the cross section and the simulated flux. The spectra are normalized via the strong resonance at 4.9 eV. The difference between the two curves is due to the presence of the background.

Simulation Studies

An intensive simulation programme[11] launched to identify the mechanism responsible for the background. All the simulations have been carried out using the general purpose Monte Carlo code FLUKA[10]. The TT2A tunnel geometry (fig.3) with all the details was modeled, in conformance to the technical drawings and civil engineering plans, apart from a couple of shielding pieces, which were not included in the technical drawings. None of these details are felt to be relevant for the calculations. However it must be stressed that the simulation did not include imperfections in the shielding, which could contribute to the observed background. In particular, no penetrations (cable trays, air and water pipes etc.) have been modeled.

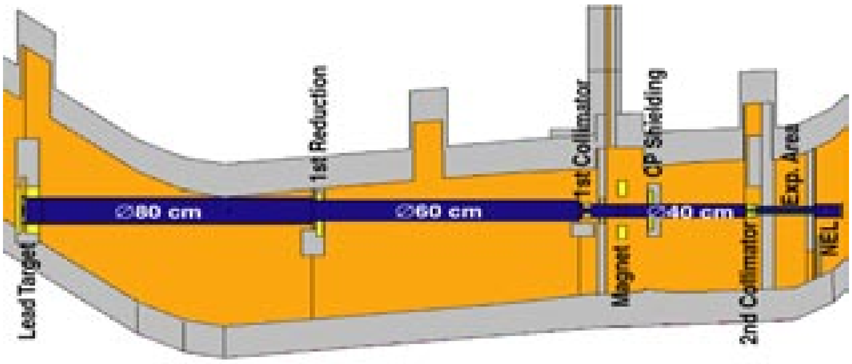

Figure 3. Top view of TT2A Tunnel Geometry used in the simulations.

Initially, a special "*simulation*" was performed to find possible weak points in the shielding of the nTOF tunnel. This was calculated using a special particle in FLUKA[10] called "*RAY*", being a straight-line trajectory through the geometry. The program tracks all the objects lying in a given direction, calculating a number of various quantities like distance traversed in each material, mass, number of interaction lengths, etc. This simulation has revealed straight paths from the target area to the experimental area where the shielding might be insufficient with a minimum range of 1400 g/cm^2 (corresponding to 5.2 m of concrete). This range is equivalent to at least 2 GeV/c energy losses by ionization for minimum ionizing particles.

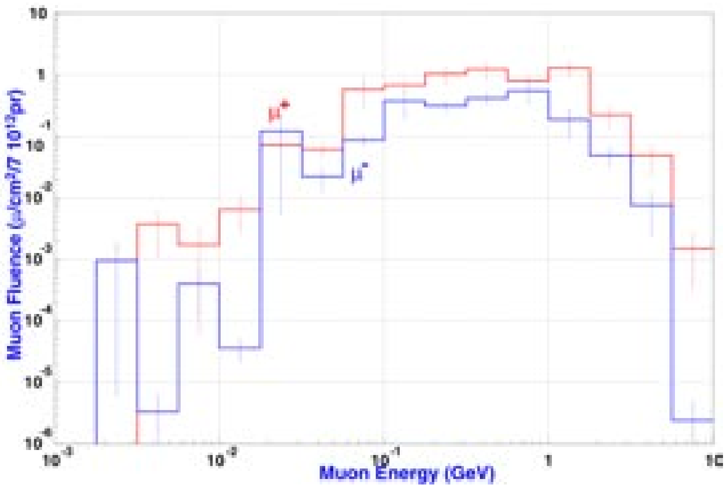

Figure 4. Energy spectrum [dμ/dln(E)] of the muons entering the experimental area.

The 20 GeV/c proton beam interacting with the lead target is a source of many charged and neutral particles[12]. The suppression of charged particles inside the neutron tube is achieved with the sweeping magnet located at 145 m. The spectrum of the muons peaks at ~1 GeV/c with a significant fraction above the 2 GeV/c ionization losses limit calculated before. Therefore, we expect to have a considerable fraction of muons penetrating the experimental area through the concrete shielding. The measurement with TLD ^{7}Li, demonstrated the presence of an ionizing signal outside the neutron tube with a strong left-right asymmetry coming directly from the target area, which was interpreted as muons. These results were validated with a subsequent simulation biased in such a way to enhance the muon fluence in the experimental area. This simulation (fig.4) showed that a significant muon component is present in the nTOF experimental area and that such a component is highly asymmetric due to the asymmetry of the material density along the tunnel. The flux of muons is enhanced up to 100 times, at the right hand side of the tunnel. The maximum muon flux is of the order of a few 10^2 $\mu/cm^2/7\times10^{12}$ protons. The muon spectrum is peaking at energies somewhat lower than 1 GeV, with a ratio μ^+/μ^- of 2.5±0.6. The maximum muon energy observed with the present statistics is around 10 GeV, consistent with the primary beam momentum (20 GeV/c), pion decay kinematics and minimum thickness along the flight direction.

According to the minimum mass calculation and the muon simulation, it was recognized that the asymmetry could be naturally explained if a penetrating component is streaming through the tunnel up to the experimental area. Hence a complete simulation of the whole setup has been performed. Due to the statistical difficulties, extensive use has been made of several variance reduction techniques, most of them specific to FLUKA[10] code. The simulation predicted a background neutron fluence of the order of a few $n/cm^2/7\times10^{12}$ protons with a slight asymmetry due to the predominant contribution of neutrons being moderated in the experimental area. This intensity is in reasonable agreement with the measurements available.

Figure 5 shows the neutron energy distribution divided into various components. The most important contribution results from the capture of negative muons in the walls surrounding the experimental area. Neutrons coming directly from the target area can be seen clearly, even though they represent a small fraction. The contribution of the Neutron Escape Line (NEL) is very small. The rest are neutrons originating mostly from interactions in the second collimator area. It is worthwhile to stress that more than 50% of the entries are thermal neutrons. The neutron spectra are quickly softened with increasing time. After a few ms only thermal neutrons are left.

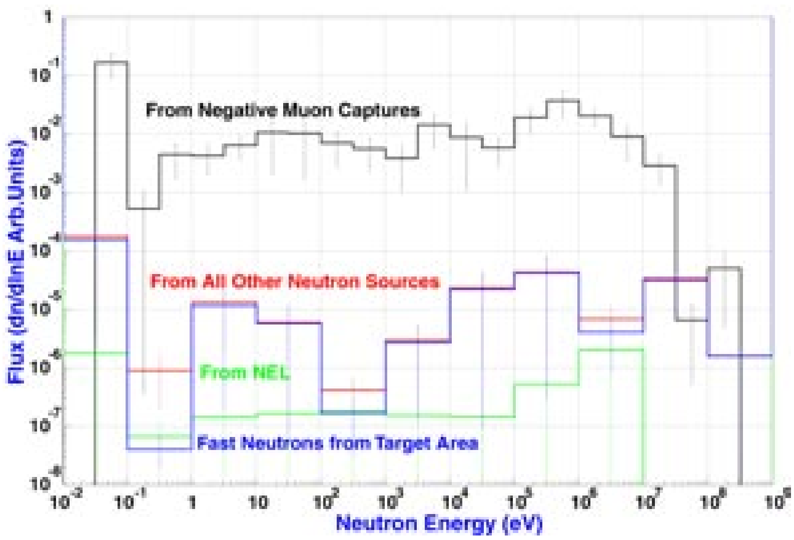

Figure 5. Neutron background fluence at the experimental area split into different sources.

Initially, the neutrons originating from muon captures are as asymmetric as their parents. However, they rapidly diffuse through multiple scattering in the walls and in the experimental room. Therefore, the time and energy averaged neutron fluence is expected to show only a slight asymmetry as indeed we measured with the neutron detector. A strong signal from stopping muon decays was observed at μs level in the C_6D_6 spectrum, due to the decay electrons.

Possible remedies

There are two ways of reducing the background at nTOF. One possibility implies devising extra shielding effective in removing the largest source of the background that is the penetrating muon component. A shielding effective against muons will be of course oversized against neutrons originating from the target area, which will disappear as well. Another approach could be a local reduction of the effect of the neutron background, by means of quick moderation and following capture. This approach will be effective whatever is the neutron source. However it will not reduce the problems associated with the muons themselves and it will not cure the fast neutron background component. The two approaches are complementary and a combination of both could be a very effective solution.

Preventing pions from decay would require much less material. However, the simulations showed that roughly 50% of the pions that will generate muons reaching the experimental hall are inside the vacuum tube at the exit of the shielding of the target area and 10% of them are still inside the vacuum pipe as far as 60 m from the proton target. Therefore a shielding in the first part of the tunnel will not be fully effective due to the impossibility of intercepting those particles still flying inside the vacuum pipe. Therefore, a 3.2 m thick iron shield has been introduced downstream of the sweeping magnet at the distance of 150 m from the lead target. This thickness corresponds to ~3.2 GeV energy loss for minimum ionizing particles, and to more than 13 interaction lengths for the most penetrating neutrons (80 - 300 MeV). A reduction factor close to 1000 can be achieved with this simple solution. Of course in reality, the overall reduction factor would be somewhat smaller, because of unavoidable penetrations in the shielding (cables, clearances, water and air pipes etc).

Experimental Studies

An experimental programme[13] was launched to verify the results obtained with the simulations and to measure the effectiveness of the shielding. The program was divided into two phases

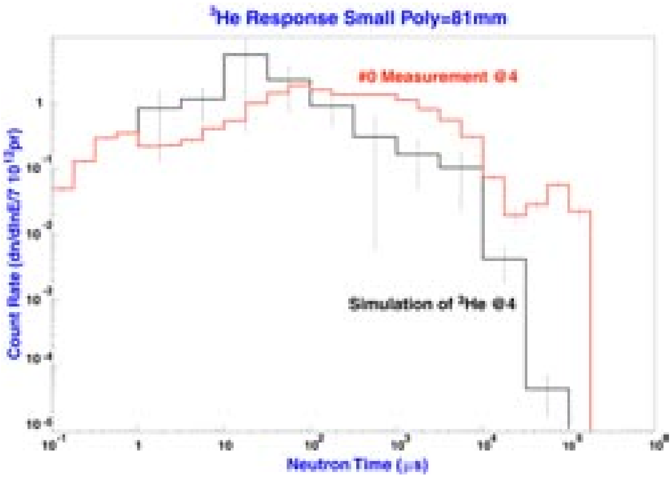

Figure 6. Background measurement with ^{3}He+polyethylene sphere and simulation.

In the **first phase** the neutron background was measured with a ^{3}He detector and the gamma background with two C_6D_6 liquid scintillators to identify the initial conditions. In most of the runs, one C_6D_6 detector was kept at a fixed position, facing the sample, while the other was moved around the experimental area. Fig. 6 shows the response of ^{3}He detector covered with a polyethylene sphere of ∅

81 mm as a function of the arrival time of the event, together with the estimation based on the simulation folded with the efficiency of the detector. The small differences between the measurement and the estimated response can be partially related to the moderation time in the polyethylene ball for fast times t < 100 μs, and for larger times t > 1 ms to an underestimation of the beam related background in the simulation.

Later, a 40 cm thick wall was mounted directly behind the 3.2 m wall separating the experimental area from the second collimator region. From this measurement a strong indication about the background mechanism was expected. The aim of the test was to discriminate between the various models of background production, since the attenuation of the background is expected to be different for neutrons and muons. For fast neutrons coming from the target the attenuation with a 40 cm wall is expected to be of about a factor 3, while for muons it is expected to be much lower. Afterwards, a beam stopper was placed inside the first collimator. The purpose was to measure the variation of the background inside the experimental area by removing any contribution from the neutron beam.

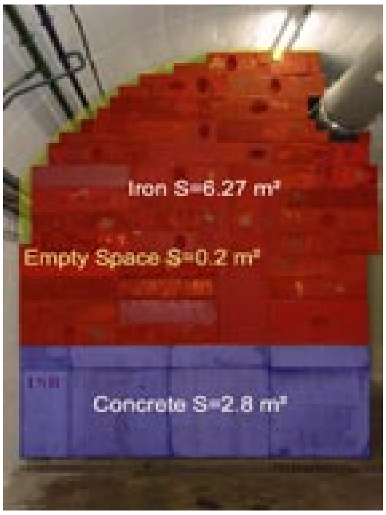

Figure 7. The 3.2 m iron wall, showing the area of concrete, iron and the empty space.

The first phase of measurements was stopped in order to mount the shielding as suggested by the simulations. The shielding consisted of a 3.2 m thick iron wall placed in the nTOF tunnel, in between the magnet and the second collimator (fig. 7). Ideally, this wall should have been made entirely of iron, and should have closed the full section of the tunnel. For technical reasons, the wall closed only the right-hand section of the tunnel, covering an area of about 2.8 m × 3.4 m, and the base was made of concrete. As shown in fig. 7, an area of about 3% of the right-hand side of the tunnel is not shielded.

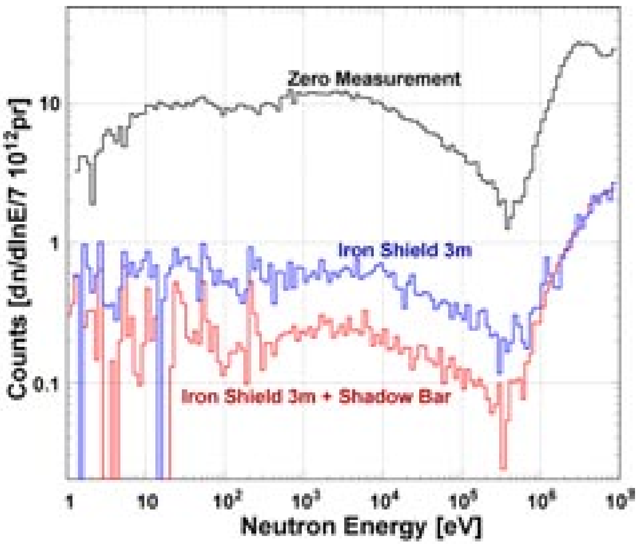

Figure 8. Comparison of the background levels, measured with the C_6D_6. The top histogram corresponds to the reference measurement. The lower one represents the residual contribution of the

muon background, after the installation of the 3.2 m iron wall, and with the beam stopper inserted in the first collimator. The beam-related component is visible in the middle histogram.

In the **second phase** of measurements data were taken with and without the 40 cm wall, and the beam stopper (fig. 8). The measurements confirmed the results from the simulations concerning the mechanism of the background production. As a result of the installation of the shielding, a strong reduction of about a factor 30 was achieved on the main background.

Background from Air activation

For high-resolution γ spectrometry, we used one HPGe detector. The detector was placed in the experimental room, near the center, 50 cm below the beam line. The γ-ray peaks present[13,14] are from ^{232}Th decay products, (U-Ra radioactive family), ^{40}K, air activation products ^{41}Ar and some spallation products ^{7}Be and ^{24}Na. The presence of short-lived activation products was evident after subtracting the γ background from the measured spectra, where the 511 keV annihilation peak and the 1293 keV ^{41}Ar γ line were clearly observed. These measurements have revealed another source of background, which is not directly beam related. The ^{41}Ar is produced by neutron capture on ^{40}Ar found in the air produced near the target and collimators area where the neutron flux is high. The solution to prevent the ^{41}Ar from arriving at the experimental area and the control room was to make the area airtight as much as possible. This has reduced the quantity of argon by a factor 10 in the experimental area, nevertheless strong fluctuations were observed due to the variation of air circulation from the tunnel.

Due to the incident angle of 10^{o} of the proton beam with respect to the neutron tube, the secondary particle cascade downstream of the nTOF target, travels a few meters in the air before reaching the surrounding concrete walls of the tunnel where it produces a considerable amount of ^{7}Be and ^{24}Na, from spallation in the air. A measurement of the activity made by TIS[15] during the nTOF operation at a distance of 70 m from the lead target, with 1/4 of the nominal proton intensity, revealed an activity of 240 Bq/m^3 for ^{7}Be and 77 Bq/m^3 for ^{24}Na. 33 hours after the shutdown none of these two isotopes was found in the air. The exchange rate of the air in the nTOF tunnel it is estimated to lie between 3 and 8 hours, due to the presence of ^{41}Ar ($t_{1/2}$ = 1.83 h) while isotopes with shorter half-life were not present. Thus, a rough approximation of the monthly release would amount to 240 MBq of ^{7}Be and 80 MBq of ^{24}Na. A simulation of the air activation was performed with FLUKA[10] assuming a 5 hours renewal of the air, resulting in an activity of 470 Bq/m^3 for ^{7}Be, and 55 Bq/m^3 for ^{24}Na, which is consistent with the measurements carried out, given all the assumptions made and the uncertainty on the used cross sections.

The solution proposed for reducing the air activation consisted on adding extra concrete shielding around the neutron tube after the lead target. Shortening this way the track length in air of the secondary particles. Two scenarios were simulated adding a 4.8 m and 14.4 m long shield around the tube. The reduction achieved was of the order of 5 and 8 respectively for both ^{7}Be and ^{24}Na. The extra shielding is currently being installed at the nTOF target.

Conclusions

The construction of the nTOF has ended in Apr. 2001 and the facility is now operational. The commissioning measurements gave results consistent with the expectations, for the neutron flux and energy resolution. The commissioning phase has shown also that radiation levels are acceptable and the target temperature is constant. The rapid energy deposition of the proton beam on the lead target produces sound waves, generating a strong audible signal. Analytic calculations and measurements have shown that possible damages due to the presence of the sound waves can be neglected.

An unexpected neutron background was observed 2 orders of magnitude higher than the calculated one. The main mechanism producing this background has proven to be the negative muon captures in the experimental area. A massive iron shielding was devised, to stop the muons, and the background has been reduced by a factor of 30.

The component of the γbackground coming from air activation (^{41}Ar) was investigated, by installing a sealing of the wall separating the measuring station from the secondary zone. This component was strongly reduced. An improvement in the shielding, together with the lining of the experimental area with borated polyethylene, could lead to a further reduction of the background. The presence of spallation products (^{7}Be and ^{24}Na) in the air from the secondary particle cascade, lead to the addition of extra shielding around the neutron tube, close to the target area.

Acknowledgments

We are grateful to CERN TIS division for the measurements and fruitful discussions concerning the radioprotection aspects of the nTOF installation. We want to thank the CRS4, for performing the calculations for the temperature behavior and the sound wave studies of the lead target. The participation of CEA-SACLAY and INFN teams to the background measurements and analysis is greatly acknowledged.

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