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Geant4 simulations of the neutron production and transport in the n_TOF spallation target

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Summary. — The neutron production and transport in the spallation target of the n_TOF facility at CERN has been simulated with Geant4. The results obtained with the different hadronic Physics Lists provided by Geant4 have been compared with the experimental neutron flux in n_TOF-EAR1. The best overall agreement in both the absolute value and the energy dependence of the flux from thermal to 1 GeV, is obtained with the INCL++ model coupled with the Fritiof Model(FTFP). This Physics List has been thus used to simulate and study the main features of the new n_TOF-EAR2 beam line, currently in its commissioning phase.

1. – Introduction and motivation

The neutron beam of the n_TOF facility is generated through spallation of 20 GeV/c protons provided by the CERN Proton Synchroton (CPS) impinging on a thick lead target. The spallation neutrons are partially moderated and travel towards the two experimental areas along two different beam lines. A detailed report on each of the experimental areas and their beamlines can be found in refs. [1, 2].

Monte Carlo (MC) simulations are an esential tool to determine fundamental features of a neutron beam, such as the neutron flux or the γ-ray background, that sometimes can not be measured or at least not in every position or energy range. Indeed, in the case of time-of-flight facilities, the energy resolution broadening, known as the Resolution Function, can not be measured and must be extracted from MC simulations. Until recently, the most widely used MC codes had been MCNP [3] and FLUKA [4]. However the Geant4 toolkit [5] has become a competitive code also in this field, especially after the work of Mendoza *et al.* [6] to adapt the evaluated neutron libraries to Geant4's format.

(*) http://cern.ch/nTOF

Fig. 1. – Dismanteled view of the main components of the spallation target as implemented in the Geant4 simulation.

2. – Geant4 simulations

The neutron beam at n_TOF is generated through spallation reactions of 20 GeV/c protons that produce hundreds of neutrons/proton in the MeV–GeV range. The main component of the n_TOF spallation target assembly is a 60 cm diameter and 40 cm thick lead core. The neutrons scaping this lead cylinder pass through several moderating layers (H_2O and borated H_2O) expanding the energy range from GeV to thermal. An illustrative view of the target-moderator assembly as implemented in Geant4 is presented in fig. 1. A more detailed description of the target geometry and the exits towards both experimental areas can be found in ref. [7].

Particles produced in the target are followed and tracked up to scoring volumes positioned at the entrance of the vacuum beam pipes where they are registered. These tally volumes, detailed in ref. [7], are the end point of our MC simulation. For both EAR1 and EAR2, we just registered the particles entering the scorers with an angle smaller than 4 degrees with respect to the beam pipe axis since the energy distribution within this small angle is isotropic for neutron energies below 1 GeV as it is proofed in ref. [7]. Under this assumption, we have propagated the neutron and gammas to the experimental areas using a geometrical transport code, explained in detail in ref. [7], that simplifies the transport along the beam line to a problem of beam optics. Geant4 v10.1 provides a wide variety of physics models that apply in different energy regimes. To perform this simulations we worked with officially released *Physics Lists* (PL) that combine the Fritiof (FTFP) model or the Quark-Gluon-String (QGSP) model above 3 GeV, with three different de-excitation models (20 MeV to 3 GeV): INCL++ [9, 10], Bertini (BERT) or Binary Cascade (BIC). Below 20 MeV, neutron induced reactions are simulated by means of the G4NeutronHP model, using the ENDF/B-VII.0 cross section library [10] in our case. Last, we have also considered the Geant4 built-in special treatment of the Thermal Scattering (HPT) of neutrons below 4 eV.

3. – Neutron flux: validation in EAR1 and results for EAR2

The energy dependence of the average neutron flux per pulse, considering the nominal proton pulse intensity of $7 \cdot 10^{12}$ protons, has been calculated from the output of the Geant4 simulation after the geometrical transport to EAR1 and EAR2. The left panel of fig. 2 compares all the studied PLs and the experimental flux measured in n_TOF-EAR1 [8]. It is clear that all the simulated fluxes overestimate the neutron flux between 15% (QGSP_INCL) and 70% (FTFP_BERT). Comparing the different PLs, the deviations in shape between the different hadronic models are clear at high energies ($E_n > 10$ MeV) and the choice of model also affects the magnitude of the flux at all energies. The combination of FTFP and INCL provides a slightly better reproduction of the shape in the high-energy part than QGSP_INCL and is the PL used hereafter for

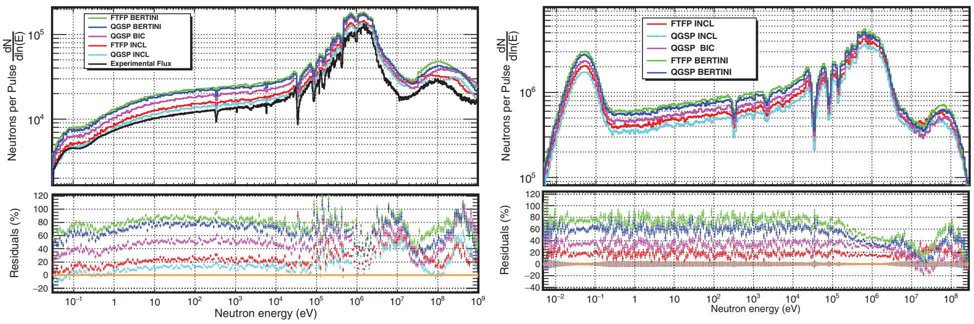

Fig. 2. – Neutron flux per pulse arriving to n_TOF-EAR1 (left), where PLs are compared to the measured flux; and n_TOF-EAR2 (right), where no experimental data are available yet.

consistency with [7]. These results show that Geant4 with the G4NeutronHP package is able to reproduce the neutron production and transport with a good ($\sim 20\%$) agreement with the data.

In the same Geant4 simulations, we estimated the flux arriving to the second experimental area (EAR2), where there is still no published experimental data. On the right side of fig. 2 we show the simulated flux for the all the studied models, showing that the differences between PLs are, as in the case of EAR1, even larger than 70% and that the smallest absolute flux is provided by QGSP_INCL. Our results indicate that the neutron flux in EAR2 is ~ 30 times larger than in EAR1. On the other hand, the high-energy limit is lower in EAR2 (~ 300 MeV) than the ~ 10 GeV reached in EAR1 because EAR2's vertical beamline does not accept the fast neutron component, forward emitted according to the kinematics of the spallation reactions. The last significant difference is the lack of a thermal peak only in the flux of EAR1, because the thermal neutrons are absorbed in a layer of borated water, which is not present in the upper exit to EAR2.

4. – In-beam γ-ray background

Photons are produced along with neutrons during the spallation and also in the capture reactions occurred along the moderation process, becoming one of the major back-

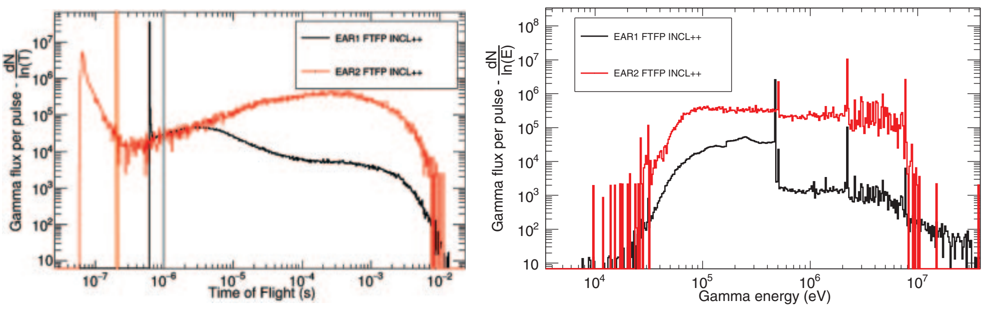

Fig. 3. – Left: Simulated γ flux per pulse obtained with FTFP INCL for both experimental as a function of the arrival time. The division between the prompt and delayed components is shown in grey (EAR1) and orange (EAR2). Right: Energy dependence of the DELAYED component of the gamma flux.

ground components in neutron capture measurements. As it becomes visible on the left panel of fig. 3, the spallation component is emitted prompt with the arrival of the proton beam and arrives to EAR1 in 650 ns while it takes just 66 ns to travel the 19.6 m flight path of EAR2 at the speed of light. The delayed component is produced mainly in neutron capture reactions, and arrives to the EARs up to a maximum of 10 ms for both areas. The energy distribution of the delayed component, shown in the right side of fig. 3, presents some signature lines: 2.2 and 7.4 MeV from capture in ^{1}H and ^{27}Al. In EAR1, where the ^{10}B is present in the moderating water, the contribution of the 2.2 MeV is heavily supressed while the 478 keV line, from capture in ^{10}B, becomes the major component of the γ-ray background.

5. – Summary and conclusions

The n_TOF spallation source has been simulated using the Geant4 toolkit. We have implemented the geomety of the target-moderator assembly in detail to obtain reliable results. The Geant4 simulation of the production of neutrons has been validated with experimental data of n_TOF-EAR1, showing a remarkable agreement in the energy dependence of the neutron flux and a good agreement ($\sim$ 20% deviation) in its absolute value. We also obtained important results for n_TOF-EAR2 that will be really helpful for feasibility studies, planning and analysis of the upcoming measurements.

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