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COMPARING GEANT4 HADRONIC MODELS FOR THE WENDI-II REM METER RESPONSE FUNCTION

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The WENDI-II rem meter is one of the most popular neutron dosemeters used to assess a useful quantity of radiation protection, namely the ambient dose equivalent. This is due to its high sensitivity and its energy response that approximately follows the conversion function between neutron fluence and ambient dose equivalent in the range of thermal to 5 GeV. The simulation of the WENDI-II response function with the Geant4 toolkit is then perfectly suited to compare low- and high-energy hadronic models provided by this Monte Carlo code. The results showed that the thermal treatment of hydrogen in polyethylene for neutron <4 eV has a great influence over the whole detector range. Above 19 MeV, both Bertini Cascade and Binary Cascade models show a good correlation with the results found in the literature, while low-energy parameterised models are not suitable for this application.

INTRODUCTION

Over the last few decades, high-energy hadron beams have been increasingly used for industrial (spallation source[1]) or medical (proton and carbon ion therapies[2, 3]) applications. However, exposure to radiation may injure those standing near the target or around the beam production installation. Indeed, the interaction of a 250-MeV proton beam (commonly used in proton therapy) with matter produces, among others, secondary neutrons whose spectrum can reach 250 MeV. The neutron energy may rise to ~800 MeV when carbon ions (400 MeV u^{-1}) are used[4]. High-energy neutrons are also present at high altitudes because of cosmic radiation[5]. To quantify the risk incurred through exposure by medical staff or pilots, dosimetric investigations have to be carried out with adequate dosemeters[6–9], as well as with sophisticated simulation codes (such as the Monte Carlo codes Geant4[10,11], MCNPX[12], PHITS[13, 14] and FLUKA[15]).

To assess the high-energy neutron doses, the dosemeters consisting of a thermal neutron detector (^{3}He or BF_3 proportional counter) surrounded by a moderator (usually polyethylene) were developed in the 1960s[16, 17] and are still being improved today (see for example Tanner *et al.*[18] and references therein). These will provide an approximation of the ambient dose equivalent[19], which is useful for quantifying the risk associated with neutron radiation, in the range of thermal to 10 MeV. Above 10 MeV, the response of these dosemeters dramatically falls, leading to an underestimation of the dose. However, the insertion of a heavy metal layer in the moderator can extend the range to GeV because of high-energy neutron nuclear reactions in this layer[20]. Subsequently, many designs were put forward, such as the LINUS developed by the CERN[21] (a layer of borated rubber and lead), the LB6411-Pb[22] from Berthold Technologies (a layer of lead) and the WENDI-II[23], Wide Energy Neutron Detection Instrument, from Thermo Fisher Scientific (a layer of tungsten). The latter was chosen for many reasons: it is affordable, lightweight (13.5 kg against 35 kg for LB6411-Pb) and thus portable, and easy to use. It has been used in many experiments[24–29] which consider the WENDI-II as a well-adapted device for radiation protection quantisation in high-energy neutron environments.

Unfortunately, high-energy field measurements are often carried out with detectors that are not fully characterised. Indeed, dosemeter calibration needs monoenergetic reference fields which do not exist today >20 MeV (even though quasi-monoenergetic neutron reference fields have became operational for a few years[30, 31]). Therefore, numerical simulations are the only way of producing the response function of a dosemeter throughout its range of use. The WENDI-II design was optimised with MCNPX by Olsher *et al.*[23]. The response function and calibration factor (the ratio of the ambient dose equivalent and the detector response for a reference field) were derived from these simulations. However, discrepancies between calculated results with different Monte Carlo codes can reach a factor of 2 or 3 (up to 5 in some cases)[32], even when the same theoretical models were used[33]. This can either lead to a conservative overestimation or a dramatic underestimation of the dose. Therefore, radiation protection devices such as the WENDI-II need to be characterised (mainly >20 MeV) with different simulation codes.

Just as Iwase *et al.*(26) did by using the PHITS code, the present work reproduces the WENDI-II response function by using the Geant4 toolkit (version 9.4.p02). This enables: (1) a comparison with the results obtained by Olsher *et al.*(23); (2) the confirmation that the WENDI-II rem meter is a good candidate to assess radiation protection quantity and (3) the demonstration that, when extended to low energy (down to thermal, as explained below), the physical models used in Geant4 (at low and high energies) are adapted to this problem. Additionally, the toolkit is downloadable as an open source from the website (geant4.cern.ch). More specifically, this work focusses on low-energy neutron transport in the device and on high-energy hadronic inelastic processes, which in turn influence the production of additional neutrons in the metal layer.

AMBIENT DOSE EQUIVALENT AND WENDI-II DESIGN

According to International Commission on Radiological Protection (ICRP) 74(19), one of the recommended operational quantities for radiation protection monitoring is the ambient dose equivalent given by

$$H^*(10) = \int h_\Phi(E)\Phi(E)\mathrm{d}E \qquad (1)$$

where E is the incident neutron energy, $\Phi(E)$ is the energy distribution of the neutron fluence and $h_\Phi(E)$ is the conversion function between the neutron fluence and the ambient dose equivalent, in units of sievert per unit fluence (Sv cm^2). The response of a dosemeter is defined by

$$R = \int C\, d_\Phi(E)\Phi(E)\mathrm{d}E \qquad (2)$$

where C is the calibration constant in units of sievert per count and $d_\Phi(E)$ is the rem meter response function in units of counts per unit fluence. A high-energy neutron dosemeter will give a response similar to $H^*(10)$ as long as the $d_\Phi(E)$ values approximately match the $h_\Phi(E)$ values.

Figure 1 shows a sketch of the WENDI-II rem meter. It is a cylindrical detector (22.86 cm in diameter by 21.0 cm long) composed of polyethylene (0.94 g cm^{-3}) and a cylindrical layer (1.5 cm thick at an inner radius of 4.0 cm) of tungsten powder (a tap density of 9.5 g cm^{-3} and an effective density of 10.624 g cm^{-3})(34). The polyethylene part inside the tungsten shell moderates the neutrons created in the tungsten before they reach the ^{3}He proportional counter. This counter is a cylindrical high-temperature ^{3}He neutron detector (two atmosphere filled) manufactured by LND, INC (LND type 252180, an effective volume of 23.95 cm^3) in which the detection of thermal neutrons can occur, mainly due to the ^{3}He(n,p)^{3}H inelastic reaction.

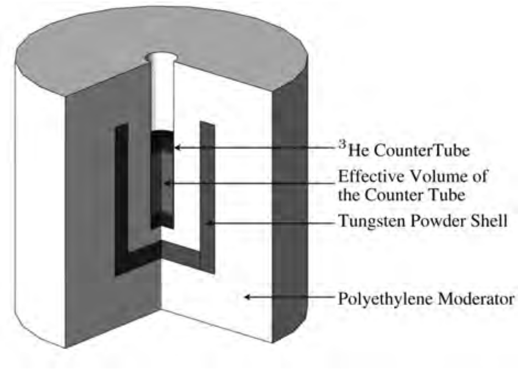

Figure 1. WENDI-II rem meter cutaway view (with courtesy of Thermo Fisher Scientific) as implemented in Geant4 simulations.

GEANT4 SIMULATIONS

The response function will be obtained by creating a simulation similar to the experimental conditions described by Olsher *et al.*(23). A monoenergetic and isotropic point source will be positioned at 50 cm from the centre of the dosemeter. Two irradiation directions are possible (side and end irradiations), but the present work only considers the side irradiation because results are similar for the other direction. As a variation reduction technique, the emission direction will be restricted to the solid angle, including the entire device (0.65 radian aperture) and a sufficient number of histories will be simulated to keep statistical uncertainties <1 % (1 sigma).

The simulation will count the number of inelastic reactions of thermalised neutrons (i.e. the number of tritium produced) in the effective volume of the counter tube (one reaction will give rise to one count), which will then be normalised to the free-in-air average fluence in this volume. Contributions of the charged particle current (protons, pions, deuterons, ^{3}He ions, pions and muons) or reactions such as ^{3}He(n,d)p, which happen >20 MeV, will not be taken into account. Indeed, their percentage is negligible (<3 % of the count rate) with regard to the large discrepancies observed in the response when different nuclear models are used(23) (up to a factor of 2, see below).

Geant4 offers the possibility of choosing or changing any physical model available in the toolkit. However, the present paper focuses on processes that have the most influence on the WENDI-II response function, that is, hadronic models of inelastic processes and neutron transport.

Low energy

Below 20 MeV, neutron high precision models (G4NeutronHP) were used. They are included in the G4NDL 3.14 neutron data library, which is based on the ENDF/B-VI (Evaluated Nuclear Data File[35]) cross-section evaluation[36]. G4NeutronHP models use a thermal treatment based on the free-gas approximation. However, <4 eV, the translation motion, vibration and rotation of the chemically bound atoms significantly affect the neutron scattering cross-sections (Figure 2) as well as the energy and angular distributions of secondary neutrons[37]. These effects were included in the Geant4 physics list by using the thermal scattering cross-section data (G4NeutronHPThermalScattering) based on the $S(\alpha, \beta)$ scattering law, recently added in Geant4 for some hydrogenous materials, such as water, graphite and polyethylene.

Olsher *et al.*[23] calculated a response overestimation of 22.5 and 42 % for 0.1 and 0.01 MeV, respectively, when the free-gas model is used instead of the $S(\alpha, \beta)$ thermal treatment for hydrogen in polyethylene. The present work reproduces these differences but Figure 3 shows that this overestimation rises to a factor of 4 for the smallest energy value of 10^{-9} MeV, which can be due to the increase in thermal scattering cross-sections when neutron energy decreases. However, the fact that thermal scattering cross-sections are higher than the elastic cross-section does not totally explain the difference in the response function. Indeed, elastic cross-section from G4NDL is different from ENDF: it has a constant value in G4NDL while it rises in ENDF when neutron energy decreases (Figure 2). Before using the thermal treatment, the ENDF values were implemented instead of the G4NDL values, while the WENDI-II response function did not really change. The influence of the cross-section values at thermal energy was not further investigated but care must be taken when dealing with thermal or cold neutron interaction with hydrogen in another material than those quoted before.

Finally, by considering the free-gas model instead of the thermal treatment, a 20 % underestimation >1 MeV occurs. This small difference cannot be explained by any straightforward physical explanation, but demonstrates that the thermal treatment influences the response function over the whole range and should be included when dealing with high-energy neutron transport.

High energy

Many works describe and compare hadronic interaction models in Geant4 up to hundreds of MeV[38–40]. Each of them has its pros and cons (with regard to attaining conservation laws, agreement with experimental data, simulation speed, etc.) and their use

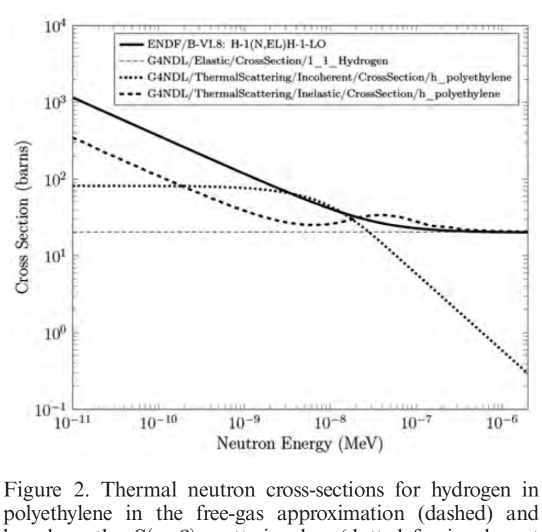

Figure 2. Thermal neutron cross-sections for hydrogen in polyethylene in the free-gas approximation (dashed) and based on the $S(\alpha, \beta)$ scattering law (dotted for incoherent elastic scattering and empty dashed for inelastic scattering). Comparison with the elastic cross section from ENDF/B-VI (solid) shows the Geant4 crude approximation for thermal neutron elastic interaction.

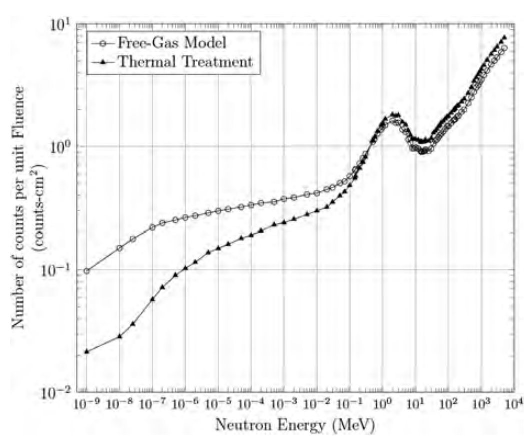

Figure 3. Number of counts per unit fluence as a function of neutron energy by considering the free-gas model (open circles) and the thermal treatment <4 eV (closed triangles). The Bertini Cascade model was used >19 MeV.

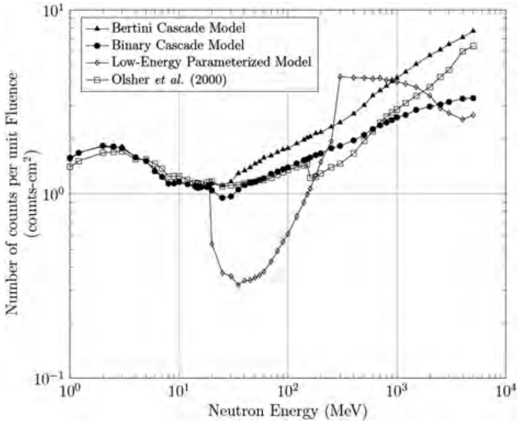

Figure 4. Number of counts per unit fluence as a function of neutron energy by using three different hadronic inelastic models: closed triangles, Bertini Cascade model; closed circles, BIC model and open diamonds, LEP models. Simulations from Olsher *et al.*[(22)] are also shown (open squares), with the courtesy of R. H. Olsher. Response functions by using Bertini Cascade and BIC models behave similarly but show discrepancies when energy increases. LEP models give a very different result compared with others.

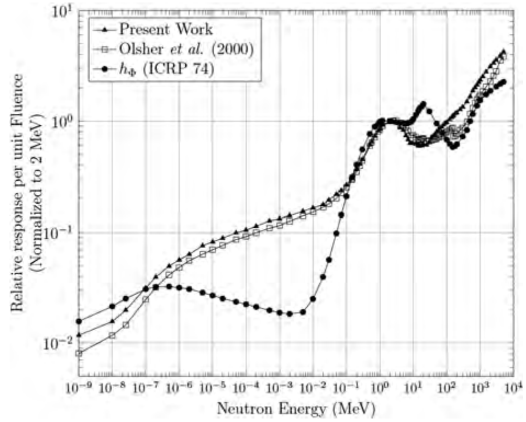

Figure 5. Relative response function per unit fluence (normalised to 2 MeV) as a function of neutron energy: closed triangles refer to present work, where the thermal treatment and the Bertini Cascade model were used and open squares refer to Olsher *et al.*[(22)], with the courtesy of R.H. Olsher. The ambient dose equivalent conversion function (normalised to 2 MeV) is also shown (closed circles).

depends on the situation at hand. In the present work, different hadronic inelastic models, such as the Bertini Cascade, the Binary Intranuclear Cascade (BIC) and Low-Energy Parameterised (LEP) models, were used for neutron energy >19 MeV to obtain the WENDI-II response function as shown in Figure 4.

Below 100 MeV, response functions by using Bertini Cacade and BIC models have the same behaviour, but the Bertini Cascade model gives a response 10 % higher than the BIC model. Above 100 MeV, this difference rises up to a factor of 2 at 5 GeV. The Bertini Cascade model gives a response function that behaves similarly to that of Olsher *et al.*[(23)] with a 50 % overestimation, while the response function by using the BIC model increases more slowly with energy. On the other hand, LEP models give a very different response function compared with others and with that of Olsher *et al.*[(23)]. LEP models were combined with the pre-compound model, applicable only <170 MeV, but did not sufficiently improve the response function at higher energy to obtain the desired behaviour.

DISCUSSION AND COMPARISON

As previously mentioned, the $^3He(n,p)^3H$ reactions in the effective volume of the proportional counter can be counted. However, the real response function in counts per unit fluence is dependent on the type of calibration performed and is affected by the wall effects in the counter tube, as well as the counter electronics. Olsher *et al.*[(23)] applied a correction factor determined by exposing the WENDI-II rem meter to a bare ^{252}Cf neutron source placed at 50 cm from the centre of the device. The comparison between the calculated response (the ^{252}Cf spectra comes from International Standard ISO 8529[(41)]) and the measured response showed a correction factor of 0.743 which then led to a sensitivity of 45.7 cpm/(μSv h^{-1}).

In the present work, the same factor was used in a Geant4 simulation of the WENDI-II exposed to a bare ^{252}Cf field, leading to a sensitivity of 48.6 cpm/(μSv h^{-1}), which is comparable to the Thermo Fisher Scientific value of 50.4 cpm/(μSv h^{-1}). However, a different proportional counter was considered (Olsher *et al.*[(23)] used a GL-2500802-NS He-3 detector from Gamma Labs) and further experiments should be carried out with the WENDI-II using the counter type 252180 from LND, INC. To overcome this calibration issue, the calculated response function was compared with that of Olsher *et al.*[(23)] by normalising it to 2 MeV in Figure 5. They used the MCNPX code (version 2.1.5) which includes the thermal treatment of neutron for hydrogen in polyethylene, cross section tables up to 150 MeV and the Dubna Intranuclear Cascade model up to 5 GeV. Both response functions behave similarly over the whole range except for an overall overestimation (15 % on average) of the Geant4 simulations. The maximum deviation (50 %) occurs between 160 and 400 MeV when the Dubna model is used in the MCNPX simulations.

The $h_{\Phi}(E)$ curve (from ICRP 74, supplemented by the calculations of Sannikov and Savitskaya[42]) is also shown (normalised to 2 MeV). In the range of 100 eV to 50 keV, the WENDI-II response highly overestimates the ambient dose equivalent, up to a factor of 8 at 5 keV. Additionally, in the range of 0.1 MeV to 5 GeV, the ambient dose equivalent is either underestimated or overestimated by a factor of 2.

CONCLUSIONS

The WENDI-II rem meter is one of the most popular neutron dosemeters used to assess a useful quantity of radiation protection, namely the ambient dose equivalent. This is due to its high sensitivity and its energy response that approximately follows the conversion function between the neutron fluence and the ambient dose equivalent in the range of thermal to 5 GeV. The simulation of the WENDI-II response function with the Geant4 toolkit is then perfectly suited to compare the low- and high-energy hadronic models provided by this Monte Carlo code. The results showed that the thermal treatment of hydrogen in polyethylene for neutron $<$4 eV has a great influence over the whole detector range. Above 19 MeV, both the Bertini Cascade and Binary Cascade models showed a good correlation with the results found in the literature, while LEP models were not suitable for this application.

The absolute response of the WENDI-II is difficult to assess because Monte Carlo simulation results are very sensitive to encoded parameters : both physical (for an incident neutron energy of 5 GeV with the Bertini Cascade model, the response value is two times higher than with the BIC model), as well as geometrical and material ones (for example, a 10 % error in the tungsten density will lead to a gap of 20 % in the response values). Further work should deal with absolute characterisation of the Geant4 hadronic models by comparing simulation results with experimental values.

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