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GEANT4 Simulation of the Shielding of Neutrons from ^{252}Cf Source

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We have done simulation studies of the neutron shielding for a ^{252}Cf source using GEANT4. For the energy distribution of the neutrons emitted from ^{252}Cf, we have assumed the Watt fission spectrum. The neutron absorption dose rates with and without the shield are estimated for three different materials of Type 304 SS, NS-4-FR and Resin-F. Among various physics models of GEANT4 for the hadronic interactions of low-energy neutrons, we have used the High Precision (HP) model, which is based on the ENDF-VI data and is able to treat elastic, inelastic, fusion and fission processes for neutrons. We have investigated the accuracy of this HP model of GEANT4 by comparing the simulation results with those from MCNP5 and experimental data.

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I. INTRODUCTION

Accurate treatments of low energy neutron interactions are essential in a wide range of industrial and medical applications. In particular, neutron shielding is of vital importance related to health and safety issues. For that reason, the validation of neutron interaction models in simulation is important. In this work, we perform GEANT4 [1] simulations for the shielding effect for low energy neutrons from a ^{252}Cf source, which is widely used as a neutron source. By comparing our results with experimental data and the MCNP5 simulation results [2], we can check the accuracy of the physics model of GEANT4 for the description of low energy neutron interactions.

II. METHOD

1. GEANT4

GEANT4 is an open source program, created by the GEANT4 collaboration [1]. It was developed for high energy physics, but nowadays is widely used for various applications. A detailed description and validation of the code can be found on the GEANT4 website [3]. In this work, GEANT4 version 9.3 was used.

2. Geometry for ^{252} Cf source and detector

We consider the experiments described in Ref. 4, where a series of experiments were made to evaluate the effectiveness of various shielding materials with a ^{252}Cf source. The average energy of neutrons from ^{252}Cf is 2.35 MeV. The spontaneous neutron fission spectrum constructed by the Watt fission spectrum [5] can be expressed as

$$f\,(E) \,\propto\, exp\left(-\frac{E}{1.025}\right) sinh(2.926E)^{1/2}, \qquad (1)$$

where E is the neutron energy in MeV.

The geometry of the source, the shield, and the detector is shown in Fig. 1 (Also see Fig. 1 in Ref. 2). The ^{252}Cf source is surrounded by a 50 x 50 x 50 cm^3 paraffin material. The neutron detector has a cylindrical shape of radius 5.25 cm and height 10 cm. The distance between the source and the center of the detector cylinder is 115 cm. The thickness of the shield is chosen to be 5, 10 and 20 cm. There is a conical shape of an opening in the paraffin so that the neutrons can pass freely and propagate through the air to reach the detector behind the shield.

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Table 1. Components and mass fractions of shielding materials used in this work.

	NS-4-FR	Resin-F	Type 304 SS
H	0.0592	0.0476	-
B	0.0094	0.0090	-
C	0.2763	0.2310	-
N	0.0198	-	-
O	0.4229	0.4825	-
Al	0.2124	0.2117	-
Si	-	-	0.0100
Cr	-	-	0.2000
Mn	-	-	0.0200
Fe	-	-	0.6650
Ni	-	-	0.1050
Zn	-	0.0182	-

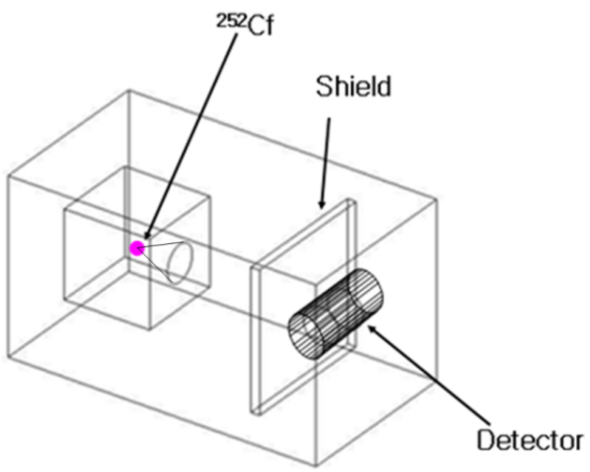

Fig. 1. (Color online) Schematic diagram showing the experimental set up.

3. Shielding materials

Three different shielding materials are used in this work. Type 304 Stainless Steel is one of the most widely used structural materials. It is a good shielding material for γ-rays but a poor one for low energy neutrons. Resin-F and NS-4-FR are resin containing boron to reduce the production of secondary γ-rays due to thermal neutrons. Resin-F is a synthetic resin that contains boron to reduce the production of secondary γ-rays by thermal neutrons. NS-4-FR is an epoxy resin that also contains boron. The components of these shielding materials and their mass fractions are listed in Table 1. Three different thicknesses of the shield, 5, 10, and 20 cm, are used for our simulations.

4. Hadronic Models

GEANT4 tool kit supports various hadronic models. Here the simulations are made with two types of models; G4Lmodel and G4HPmodel. Each model has four physical processes for neutrons; elastic, inelastic, fission and capture.

Table 2. GEANT4 hadronic models and processes used in this work.

Process	G4Lmodel	G4HPmodel
Elastic	G4LElastic	NeutronHPElastic
Inelastic	G4LENeutronInelastic	NeutronHPInelastic
Fission	G4LFission	NeutronHPFission
Capture	G4LCapture	NeutronHPCapture

G4Lmodel is a parameterized model and is constructed by GEISHA [6]. This model covers a broad energy range up to 10 TeV. On the contrary, G4HP (High Precision) model is a data driven model. The energy coverage of the HP model is from thermal energies to 20 MeV. The HP model is based on the data formats of ENDF/B-VI. This model includes cross sections and final state information for elastic, inelastic scattering, capture, fission and isotope production. Table 2 lists the names of the hadronic models used in this work.

III. RESULTS

1. Flux to dose rates

By running GEANT4 simulations for the geometrical set-up as shown in Fig. 1, we calculated the number of neutrons that reach the detector surface after passing through various shielding materials and air. To estimate the human biological dose equivalent rate, one often uses a conversion factor which converts the neutron flux to human biological dose equivalent rate. The dose rates were calculated by using the flux to dose conversion factor with a unit of (rem/hr)/(particles/$\mathrm{cm}^2 \cdot \mathrm{s}$) from the National Council on Radiation Protection and Measurements (NCRP-38) standard [7].

2. Relative dose rates

The relative dose rate is defined as the ratio of the dose rate with the shield to the dose rate without the shield. The calculated relative dose rates are plotted in Fig. 2. Statistical errors of simulations are less than 0.5%. Figure 2 shows that our results obtained with G4HPmodel based on ENDF/B-VI agree with the MCNP5 results [2] and experimental data [4]. The difference between our results from G4HPmodel and the experimental results is less than 5%. The results from G4HPmodel, MCNP5 and the experimental results overlap more or less with each other and are difficult to distinguish for all three materials as seen in Fig. 2. However, if we use G4Lmodel, which is a parameterized model, our results differ by about 20% compared to the experimental results for the materials NS-4-FR and Resin-F. For the case of Type 304 SS, the results from G4HPmodel and G4Lmodel are in good agreement with each other.

The materials NS-4-FR, Resin-F and Type 304 SS are predefined in GEANT4. The fact that the results from G4Lmodel and G4HPmodel are very close to each other

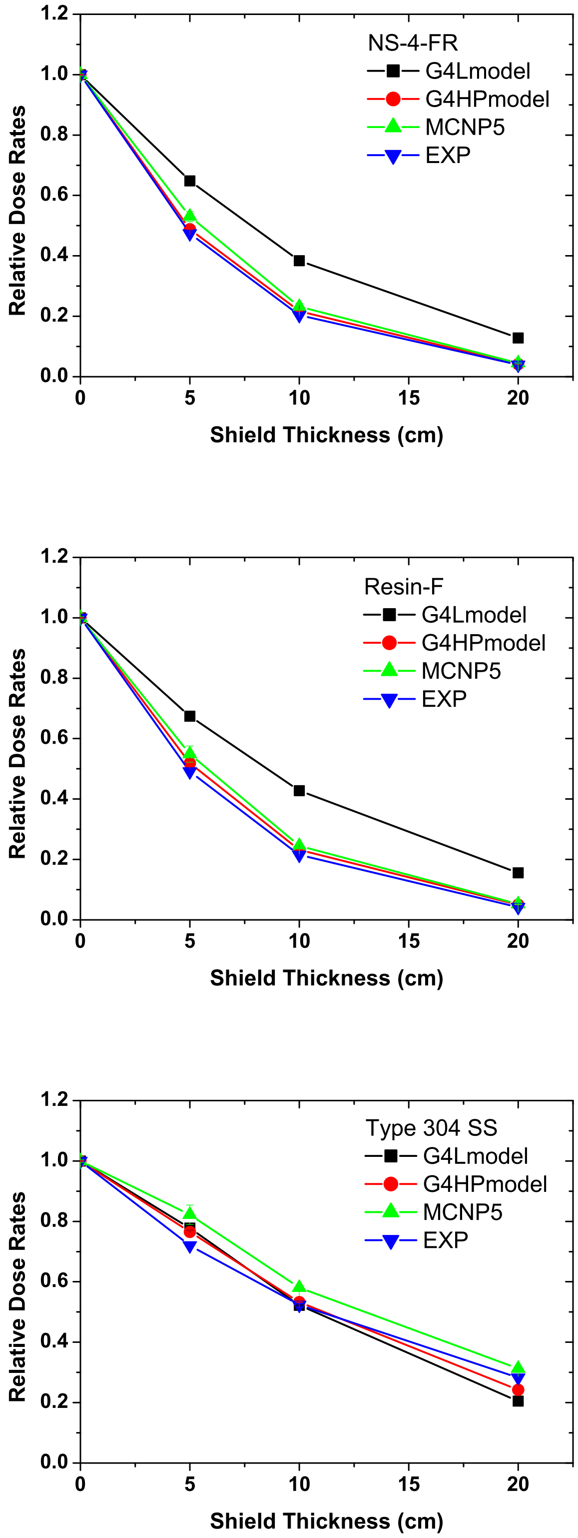

Fig. 2. (Color online) Relative dose rates are plotted against the shield thickness.

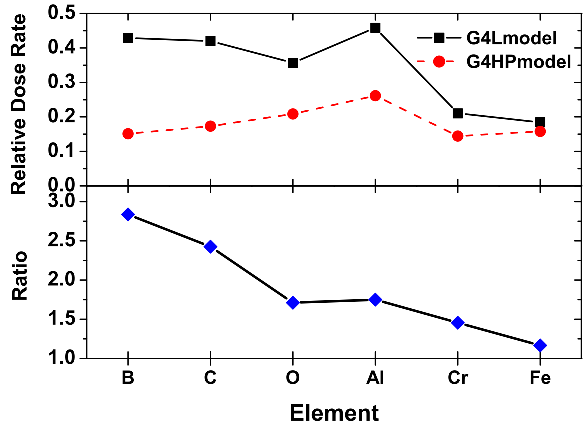

Fig. 3. (Color online) Relative dose rates are plotted for different shield elements in the upper panel, and the ratios of the relative dose rate with G4Lmodel to the relative dose rate with G4HPmodel are plotted in the lower panel.

for Type 304 SS whereas they are significantly different for NS-4-FR and Resin-F implies material dependence of the results.

We looked into this material dependence by running each process in Table 2 for the elements B, C, O, Al, Cr and Fe. We chose these elements because they are the major components of these materials. For this investigation, we considered the neutron beams as a pencil beam with the same energy distribution as in Eq. (1). Now each shield material consists of a single element. We choose 10 cm for the thickness of each shielding element, because a large difference is observed between G4Lmodel and G4HPmodel for this thickness as seen in Fig. 2. In the upper panel of Fig. 3 we show the relative dose rates calculated by G4Lmodel (squares) and G4HPmodel (circles). For all elements except for Fe, there are large differences in the values of the relative dose rates calculated by G4Lmodel and G4HPmodel. We take the ratios of the relative dose rate with G4Lmodel to the relative dose rate with G4HPmodel and plot them in the lower panel. It shows that the results from G4Lmodel and G4HPmodel differ by 2.8, 2.4, 1.8, 1.8, 1.5 and 1.2 for B, C, O, Al, Cr, and Fe, respectively. This clearly shows G4Lmodel needs improvements for the elements B, C, O, Al and Cr.

3. Neutron fluence

Let us now consider the neutron shielding for different shielding materials of different thickness as a function of neutron energy. We have calculated the neutron fluence on the source side of the shielding material and the detector side of the shielding material, where the source side refers to the surface of the shield facing the ^{252}Cf source in Fig. 1 and the detector side means the surface of the shield facing the neutron detector. The solid curves in Fig. 4 denote the neutron fluence on the source

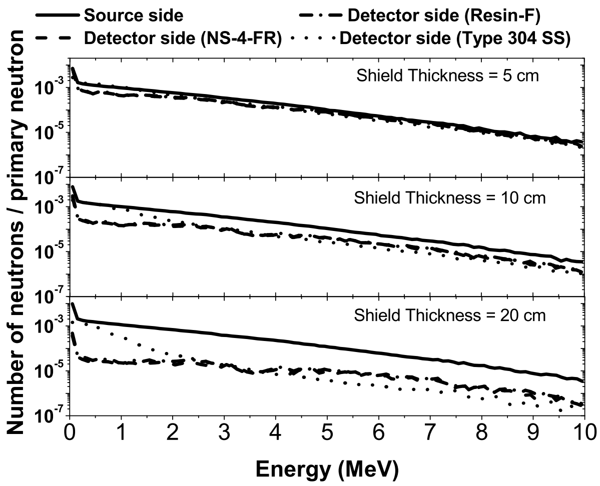

Fig. 4. The number of neutrons calculated on the source side and the detector side of the shielding material is displayed, when we assume that one neutron is emitted per second from the neutron source.

side as given by Eq. (1). The dashed, dash-dotted, and dotted curves represent the neutron fluence on the detector side of the shield made of NS-4-FR, Resin-F, and Type304SS, respectively. (Note that the dashed and the dash-dotted curves overlap with each other.) As the thickness of the shield increases, the neutron fluence on the detector side decreases as shown in Figs. 2 and 4. When the thickness of the shield is 5 cm, only 20 $\sim$ 50% of shielding can be achieved. To reduce the number of neutrons by one order, we need thickness of 20 cm as can be seen in Figs. 2 and 4. For neutron energies below about 2.5 MeV, which is the average energy of neutrons from ^{252}Cf, the numbers of neutrons for the shield materials NS-4-FR and Resin-F are smaller than that for Type 304 SS. This is due to the presence of boron in NS-4-FR and Resin-F because boron captures low energy neutrons very well. For energies higher than $\sim$2.5 MeV, Type 304 SS has a better shielding ability compared to NS-4-FR and Resin-F, because boron in NS-4-FR and Resin-F can shield low energy neutrons, but is not effective in shielding high energy neutrons.

IV. DISCUSSION

We have calculated the neutron shielding rates using GEANT4 with two sets of hadronic models, G4HPmodel and G4Lmodel. We find that G4HPmodel based on nuclear data ENDF-VI describes the experimental relative dose rates quite well for all three shielding materials considered in this work. Discrepancy between experimental results and our simulation with G4HPmodel is less than 5%. On the other hand, G4Lmodel is found to be an inaccurate model for NS-4-FR and Resin-F materials, especially for C, O and Al elements. Thus, further improvement of G4Lmodel is needed for these light elements.

We also find that the thickness of the shield needs to be about 20 cm to reduce the number of neutrons penetrating the shields by one order of magnitude. The materials NS-4-FR and Resin-F can shield the neutrons of energy less than $\sim$2.5 MeV much more effectively than Type304SS, while Type304SS is a more effective shield material for neutrons of higher energies.

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