Geant4 Results for "inter-comparison problems of neutron attenuation"

Tatsumi Koi
SLAC National Accelerator Laboratory, Menlo Park US

Abstract

Geant4 is a toolkit for the simulation of the passage of particles through matter. To demonstrate its capability in shielding applications, we have submitted Geant4 results to the SATIF "Inter-comparison Problems of Neutron Attenuation" since 2006. Because Geant4 takes the toolkit approach, the user is allowed flexibility in choosing not only geometry but also physics processes as implemented in a physics list. For the benefit of users, the "Shielding" physics list, which we used in the comparison, is included in the release of Geant4. The latest Geant4 result obtained by using this physics list is measured against the experimental data of the BNL AGS benchmarks and presented in this paper. The agreement with data was found to be slightly worse than that for SATIF-10. After a detailed investigation, we found that the difference is mainly caused by the change of internal nucleon-nucleon cross-section in a cascade model. We confirmed that by switching back to the original cross-section, the agreement with data returns to the level of SATIF-10. Besides this physics list, the current Geant4 provides about 20 so-called reference physics lists and the results from these, together with brief explanations about the character of each list, are also presented.

Introduction

The Geant4 toolkit [1] provides a complete set of class libraries for Monte Carlo simulations of particle interactions in matter. Geant4 is used in many research fields, such as high-energy physics, nuclear physics, astrophysics, space engineering, non-destructive inspection, detector development, environmental research, and medical physics. In order to demonstrate Geant4 capability in radiation protection and shielding calculations, we have participated in the "Inter-comparison of Medium-Energy Neutron Attenuation in Iron and Concrete" project since SATIF-8 [2] [3] [4]. Because Geant4 is designed as a toolkit, it does not include a default application. Users must implement a few classes to build a fully integrated application. One such mandatory class is the "Physics List" where users assemble the physics processes required for the simulation. However, preparing a proper physics list for an application is not an easy task even for experienced users; therefore several "reference" physics lists have been provided as part of the release. One of these, the "Shielding" physics list which has been in the release since v9.4 was used in this comparison.

While preparing the Geant4 result for the SATIF-11 comparison, two problems were noticed. One is related to scoring and the other is associated with physics performance. In this paper, we will explain these problems and their solutions, and show the results of the Geant4 in comparison to the experimental data in the BNL AGS benchmarks. Results from using other reference physics lists in Geant4 are also presented with brief explanations about the character of each list.

Calculation of BNL AGS benchmarks

Comparisons were made to the data from the BNL AGS shielding experiment. 2.83 GeV and 24 GeV protons beams irradiate a mercury target and secondary neutron fluences in the shielding material of concrete and iron were measured. Details of the experiment are available in [5]. The reaction rates of ^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,6n)^{204}Bi were provided by the co-ordinator of the inter-comparison.

The problem in weight calculation

While performing the comparison, we observed unexpected bumps in the result mainly in the deep penetration region. After some investigation, we found that the latest version of Geant4 (v9.5.p01) has a problem in the weight calculation. Analogue calculations (every particle has weight = 1) return correct answers but once we activate variance reduction techniques such as geometrical importance biasing, weight windows and Russian roulette, strange results appear. The problematic code was identified and a fix was also provided. However, to maintain to ability of users to reproduce our result we decided to do our calculation using Geant4 v9.6 beta which does not have the problem. The fix will be included in a future patch release of Geant4.

Results from Geant4 9.6 beta

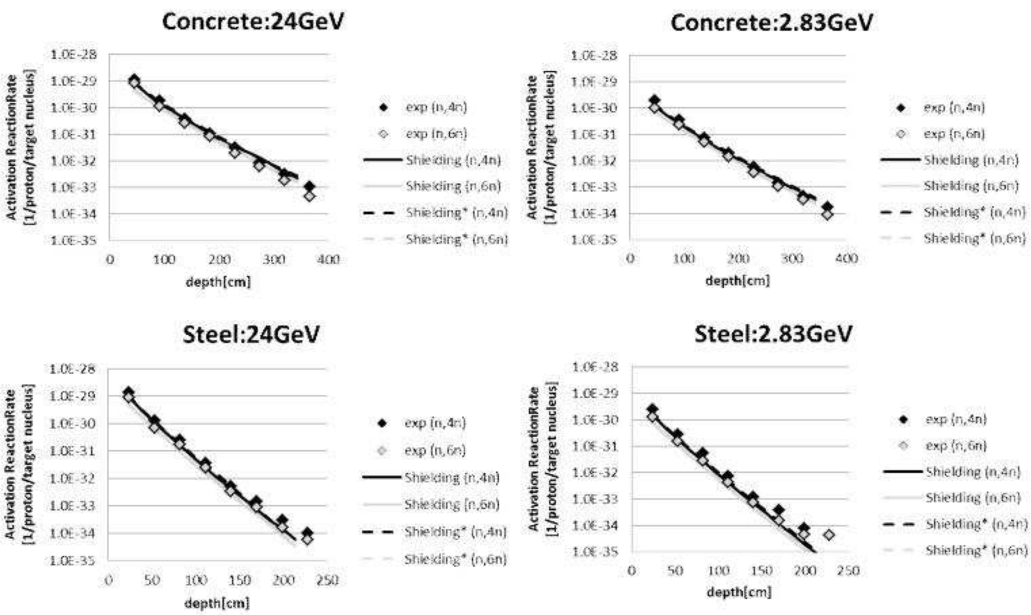
Figure 1 shows Geant4 results of the comparison with the benchmark. The solid lines are results from Geant4 v9.6 beta with the shielding physics list and the broken lines are Geant4 results with some modification of the original version. We will describe the modification later. Reasonable agreement can be seen in the plots. We defined a quantitative measure representing the level of agreement between data and simulation. The value (X) is defined by the following equation:

$$X = \sum_{i=1}^{n} \mathrm{abs}\left(\log\left(\frac{x_{sim\_i}}{x_{data\_i}} \right) \right) \quad (1)$$

In Figure 2 we compare the Geant4 results to the SATIF-10 benchmarks. It shows that the original result from Geant4 9.6 beta becomes worse than the result at SATIF-10 especially in the steel case.

While checking for possible changes which may have caused this difference, we found that internal nucleon-nucleon cross-sections in the Bertini-style cascade were modified. They were changed from their original values to the free-space PDG values. The code was then modified to switch back to the original values. Broken lines in Figure 1 and bars filled by checker board pattern in Figure 2 represent the results of this modification. In steel shielding cases, the agreement with data improves, returning to its previous level or even improving slightly at 24 GeV. In the concrete shielding cases, there is no improvement in the new result; however, the absolute agreement is much better than in the steel cases. Several other developments may potentially impact the results, but we conclude that most of the difference comes from the change of the internal cross-sections. The modification will be included in the next release of Geant4.

Figure 1: Geant4 result for inter comparison of BNL AGS benchmark



Results from other reference physics lists

Many reference physics lists are provided in the Geant4 release. One of them is the shielding physics list, which we have already discussed. We also compare to the BNL AGS benchmark several other reference physics lists and test their X values. FTFP_BERT, QGSP_BERT, QGSP_BIC and QBBC were selected for the test. FTFP_BERT uses the Fritiof string model at high energies and the Bertini-style cascade at medium energies, that is, below the string formation energy, and at low energies below the resonance region. This physics list is quite similar to the shielding physics list, differing mainly in the selection of cross-section data sets [6] and in the use of neutron HP model for neutrons below 20 MeV. The Quark Gluon String model is used for high-energy interactions in QGSP_BERT, QGSP_BIC and QBBC physics lists. The former two physics lists use the Bertini-style cascade and the Binary cascade for the medium- and low-energy interactions respectively. QBBC uses the Bertini-style cascade at medium energies and the Binary cascade at low energies. None of these physics lists use Neutron HP model for low-energy neutron transportation below 20 MeV, which the Shielding physics list uses, but because the thresholds of the reactions

^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,6n)^{204}Bi, are 22.6 and 38.1 MeV, respectively, this is not important in the comparison. Figure 3 shows X values from these physics lists together with results from shielding physics list. The result from the shielding physics list is better than most of the others, but QBBC gives comparable results and even better ones in concrete shielding cases.

Figure 2: The X values of the Geant4 results for BNL AGS benchmark at SATIF-10 and v9.6 beta

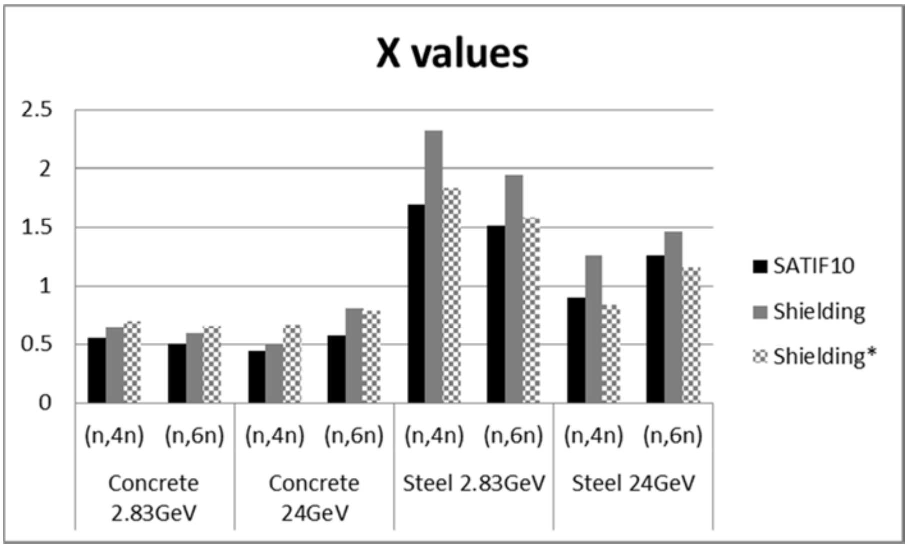
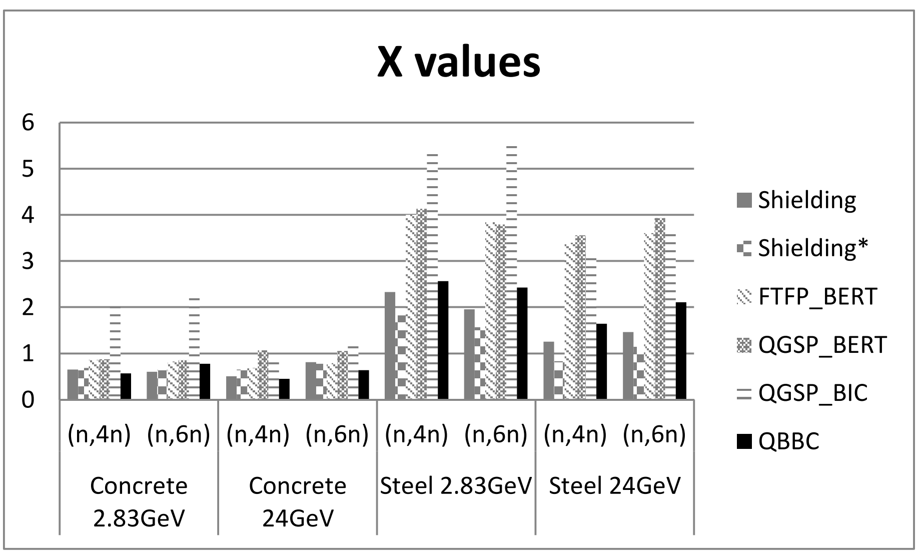


Figure 3: The X values among reference physics lists in Geant4



Conclusion

The Geant4 result for the inter-comparison is presented. Because of weight calculation problems in the latest official release of Geant4 v9.5.p01, we use Geant4 v9.6 beta with its shielding physics list for the comparison. BNL AGS benchmark results become slightly worse than the result at SATIF-10. The differences come mainly from the change of internal nucleon-nucleon cross-sections in the Bertini-style cascade and once the cross-sections are returned to their original values, most differences disappear. We also calculate the benchmark for several other reference physics lists. The agreement to the data becomes worse than the shielding physics list in most cases. However, comparable results are achieved when using the QBBC physics list. These changes will be reflected in the future development of Geant4.

References

[1] S. Agostinelli *et al*. (2003), "Geant4: a Simulation Toolkit", *Nucl. Instrum. Meth.* A 506 250.J. Allison *et al*. (2006), "Geant4 Developments and Applications", *IEEE Transactions on Nuclear Science* 53 No. 1, 270-278.

[2] H. Hirayama *et al*. (2006), "Inter-comparison of the Medium-Energy Neutron attenuation in Iron and Concrete (6)", *Proceedings of the Shielding Aspects of Accelerators, Targets and Irradiation Facilities – SATIF8*, Pohang Accelerator Laboratory, Republic of Korea, 22-24 May 2006, pp.237-250.

[3] H. Hirayama *et al*. (2010), "Inter-comparison of the Medium-Energy Neutron attenuation in Iron and Concrete (7)", *Proceedings of the Shielding Aspects of Accelerators, Targets and Irradiation Facilities – SATIF-9*, ORNL, USA, 21-23 April, 2008, OECD/NEA, pp. 261-274.

[4] H. Hirayama *et al*. (2010), "Inter-comparison of the Medium-Energy Neutron attenuation in Iron and Concrete (8)", *Proceedings of the Shielding Aspects of Accelerators, Targets and Irradiation Facilities – SATIF10*, CERN, Switzerland, 2-4 June 2010, OECD/NEA, pp. 217-233.

[5] N. Matsuda *et al*. (2008), "Analyses of Benchmark Problems for the Shielding Design of High Intensity Proton Accelerator Facilities", *JAEA-Technology* 2008-030.

[6] T. Koi (2010), "A Geant4 physics list for shielding calculation", *Proceedings of the Shielding Aspects of Accelerators, Targets and Irradiation Facilities – SATIF10*, CERN, Switzerland, 2-4 June 2010, OECD/NEA, pp 407-412.