Increased transparency in simulations of measurements for nuclear disarmament verification

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Abstract:

For many safeguards and disarmament verification purposes computer codes are used to simulate and develop different measurements techniques. Often there are some access barriers for the used software (e.g. export controls, high costs for source code). Greater transparency could be provided if a software’s source code is made public to everyone dealing with results of calculations. Today, this level of transparency is not required for most applications. But it seems clear that greater transparency of codes will enhance credibility and confidence to foster further steps in nuclear disarmament and non-proliferation.

This paper aims to show the utility of the Monte Carlo code framework GEANT for such purposes. Here we concentrate on the simulation of neutron multiplicity counting measurements that will be necessary for nuclear warhead authentication. We simulate the response of a Plutonium Scrap Multiplicity Counter for a Cf-252 source as well as different masses of plutonium. The results will be compared to other simulation codes and measurement results. We analyse differences with the goal to outline possible modifications for GEANT.

Keywords: disarmament verification, transparency, GEANT, multiplicity counting

1. Introduction

For any activity in the field of disarmament or non-proliferation increased transparency increases trust and confidence among states and other actors. Such an increase in transparency can be achieved by providing data, opening up facilities to inspectors, having observers present at important processes, and many other means. In the process of verification, declared information is checked by states or other actors, like the IAEA. To ensure that other parties can trust the outcome of verification, this process has to be as transparent as possible too.

During all these described activities computer codes are used to simulate results. In many cases simulations are being conducted during the development and design phase of a measurement device. It is also possible that the execution of measurements could only be done by using simulation codes in parallel. Finally, it might be possible to falsify declarations without doing measurements simply by applying simulations (e.g. calculate possible plutonium stockpiles with reactor burnup calculations). Transparency for all these types of simulations could be increased provided that a software code would fulfil the following two requirements:

1. Free (no cost, no license limitations) and easy access to the software
2. Free (no cost, no license limitations) and easy access to the source code of the software to ensure “verification of the verification”

Both requirements should be met at least for the actors involved in a verification process. But greater transparency and increased trust could be reached if every interested actor could access software and source code. An additional third requirement could also address simplified ways to guarantee the
correct function of a software.

For software codes frequently used for nuclear verification purposes all these requirements are often unmet. Access barriers can be export controls, restricted source code access or high costs for software and/or source code. Other simulation codes like Geant4 [1] meet at least two of the described requirements – it is available free of charge in source code form. However, a code like Geant4 is less often used for verification purposes so far.

In this paper we examine Geant4 capabilities for neutron multiplicity counting for nuclear disarmament verification. Neutron multiplicity counting is one of the measurement techniques used for the verification of warhead dismantlement and could provide inspectors with the means to verify that a nuclear weapons possessor dismantles its nuclear arsenals.

Increasing transparency increases trust in a verification process. However, in the case of nuclear disarmament verification the level of transparency and the possibility to share information is limited by the necessity for secrecy due to nonproliferation. Hence the use of information barriers is often discussed to restrain access to sensitive information. But their design should be as transparent as possible. Neutron Multiplicity Counting could be used to assess the plutonium mass of a nuclear warhead (an attribute of the item). To help ensuring a transparent development of an information barrier which uses neutron multiplicity counting Geant4 could be useful and versatile tool. This paper examines Geant4 capabilities for the usage for Simulations of Neutron Multiplicity Counting.

2. Description of Detector and Simulated Measurements

To test the applicability of the Geant4 for neutron multiplicity counting we modelled the „Plutonium Scrap Multiplicity Counter“ [2], [3]. This detector has been used to estimate the amount of plutonium on scrap materials, but can be used to estimate plutonium masses in general. The detector consists of 80 He3 Tubes in four concentric rings surrounding a cylindrical cavity. The tubes are placed in a High Density Polyethylene (HDPE) block for neutron moderation. The signals are processed by 19 Pre-Amplifiers and later in a multiplicity shift register. The cavity has a diameter of 20 cm and a height of 40 cm. The detector has a very flat axial and radial efficiency profile. We derived the dimensions from drawings in [2] and implemented a model in Geant4. The model can be seen in Figure 1.

Figure 1: Geant4 model of the Plutonium Scrap Multiplicity Counter, view from above and from side. Neutron tracks for 5 spontaneous fission events are shown in red.

1 In fact, it is only possible to estimate the effective Pu240 mass. The total mass can be calculated given that one knows the isotopic composition of the plutonium.
The multiplicity distribution cannot be measured directly due to (necessary) moderation and neutrons originating from other events than spontaneous fissions. Instead, incoming neutron detection events are stored in a multiplicity shift register. After the measurement, the detector electronics directly provides the user with information about the factorial moments of the multiplicity distribution.

Similarly, our simulation has been divided in two parts. The particle transport routines of Geant4 are used to simulate the neutron sources in the detector as well as the neutron transport through the material. Neutrons are tracked until absorption in He3 tubes or other events occur (e.g. leaving the detector geometry). The time information of the absorption processes in the tubes is stored as a neutron pulse train. For the second part, the calculation of the factorial moments, an additional Geant4 library is currently programmed by the authors to carry out pulse train multiplicity analysis in analogy to the analysis carried out by the detector electronics in the PSMC. This library is still work in progress and will be presented elsewhere.

3. Code framework GEANT4

Geant4 is a Monte Carlo toolkit, mainly developed for high energy nuclear physics. It is a standard code written in C++ and widely applied in physics research, but rarely used in the field of disarmament, nuclear engineering and reactor physics. To carry out neutron multiplicity calculations with Geant4, mainly three requirements have to be met: good neutron transport capabilities (including thermal neutrons), definition of spontaneous fission sources with correct multiplicities, and capabilities to simulate \((\alpha, n)\) reactions\(^2\).

3.1. Neutron transport capabilities

The main requirement to adequately simulate a neutron multiplicity counter is the availability of data for thermal and fast neutron reactions. Geant4 includes data driven models for neutron transport below 20 MeV based on the ENDF-B VII cross-section evaluations, the so-called High Precision (HP) neutron cross sections. These have to be included in the physics list of the Geant4 model. However, by default no data is included in Geant4 for elements with Z>92. To simulate neutron transport in plutonium we used data libraries (JEFF 3.1, ENDF/B VII) in the Geant4 format, which have been converted by Emilio Mendoza and Daniel Cano-Ott from the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain and are available through the website of the IAEA [4]. These libraries also include elements for Z>92. They also fulfill all transparency requirement as they are freely available.

3.2. Source Definition for Spontaneous Fission

As important as neutron transport is a correct simulation of the source. To calculate factorial moments from the simulated pulse train the spontaneous fission multiplicity distribution has to be adequately simulated. Geant4 includes capabilities to simulate particles released by the radioactive decay of different isotopes. This is possible also for isotopes with Z>92, if special variables are set. However, by default it does not include spontaneous fission reactions.

Geant4 provides a preliminary hook to include a spontaneous fission source library provided by a group at the Lawrence Livermore National Laboratory [5]. This special library for nuclear fission in Monte Carlo calculations includes data on spontaneous fission multiplicities for various actinides, from which the actual number of particles for each fission can be sampled with a user defined random number generator. It also generates the energy distribution of the released neutrons and gammas in a spontaneous fission event.

To these functionalities we added the capability to use a combination of different isotopes as a single source, which will be necessary for material compositions consisting of different plutonium isotopes and supposedly other actinides. We also added a routine to combine the spontaneous fission source

\(^2\) If oxygen or other low-z elements are present these reactions contribute significantly to the neutron background because of the \(\alpha\) decay of plutonium.
with the standard Geant4 radioactive decay source, so that alpha decay and spontaneous fission can be used as a combined source.

As the pulse train multiplicity analysis depends also on the specific timing of neutron captures, it is important to adequately sample source events during a specific time interval (e.g. the real measurement time). We sample the time of a source event by using the uniform random number generator of Geant4 and the following function, in which \( u \) stands for the random number uniformly distributed between 0 and 1 [6]:

\[
t = -\frac{1}{\lambda} \ln (\beta + u(\alpha - \beta))
\]

with

\[
\alpha = \exp(-a\lambda) \\
\beta = \exp(-b\lambda)
\]

In those formulae, \( a \) and \( b \) describe the time interval (e.g. 0 and 900s for a measurement duration of 900s) and \( \lambda \) is the decay constant of the respective decay.

3.3. Simulation of \((\alpha, n)\) Reactions

The third capability that Geant4 should meet to yield good results to simulate neutron multiplicity measurements is the integration of \((\alpha, n)\) reactions. Geant4 comes with a model to simulate these reactions with low-z materials, the Binary Light Ion Cascade Model.

In other transport codes like MCNP there is no direct implementation of \((\alpha, n)\) reactions. MCNPX can transport alpha particles but lacks standard \((\alpha, n)\) cross section tables or models. One can only implement an additional neutron source definition based on precalculated neutron spectra from codes like SOURCES4C [7]. In MCNP-PoliMi [8] neutron production from \((\alpha, n)\) reactions is implemented by special sources for oxides of different plutonium isotopes, for AmO\(_2\), AmLi, and AmBe mixtures.

![Figure 2: Comparison of Geant4 simulated \((\alpha, n)\) with measurement results in [9,10]. The lines are only drawn to guide the reader.](image)

We simulated the reactions with Geant4 using a large sphere of material with an isotropic neutron source in the center. We counted the number of neutrons that were produced by the bombardment of \( \alpha \) particles. Figure 2 shows the results for different \( \alpha \) energies and for spheres of beryllium and boron in its natural isotopic composition. The measured values were taken from [9,10].

The simulated values reproduce fairly good the energy dependence of the measured values. However, the total numbers are overestimated roughly by a factor of two. For \( \alpha \) particles with an energy of 5.2 MeV which corresponds to the energy of particles produced by the decay of Pu240, measurements for a beryllium target show the release of 65 neutrons per million \( \alpha \) particles. The simulations show 110...
neutrons per million $\alpha$ particles. Similar results were obtained for other energies and materials. This leaves room for future improvement, by either circumventing the simulation of neutron production by adding a specific neutrons source based on the measured values for every material that undergoes the reactions or to improve the Geant4 model for ($\alpha$, n). The latter possibility would increase the applicability of the code for many different other problems.

4. Detector Efficiency for Cf-252 measurements

With the model of the PSMC and the spontaneous fission source as specified above, we calculated the detector efficiency for a Cf-252 source at different axial positions in the detector cavity. The results are shown in Figure 3.

![Figure 3: Comparison of detector efficiency measurements [11] with simulation based on two sets of neutron cross section based on Geant4 and [4].](image)

We did two sets of calculations, using the neutron reaction data coming with Geant4 as well as the data provided by Mendoza et al. [4]. In general, both data libraries show similar results – the differences can be taken as a measure of the statistical error produced by the simulation. Both calculations show a slight underestimation of the detector efficiency compared to the measurements [11]. But given that the statistical error of the simulations is around 0.5 %, it is possible to conclude that the simulations are in reasonable accordance with the measurements.

5. Conclusion

Transparent software tools are required for non-proliferation and disarmament verification applications. Geant4 can fill in here, as other simulation codes generally do not meet the two requirements for transparent simulation software: free and easy access to the software and the source code. The third requirement – verification of the function of the code itself – will remain difficult and is a field for further development.

For Geant4 we have shown that it is generally feasible to simulate neutron multiplicity measurements using this code. It is possible to simulate different source materials and the particle transport. The necessary neutron reactions are implemented very well, especially using the cross section data provided by Mendoza et al. The deficiencies found for ($\alpha$, n) can be overcome by implementing special neutron sources for the reactions or by improving the Geant4 reaction model in the future. We started to develop a pulse train analysis class that already shows good results, but will need more development. Further research also has to be conducted to validate the simulation capabilities, by applying the pulse train analysis library and by simulating other detector types and probe geometries.
References


