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Background simulations for the SuperCDMS experiment – Efficient GEANT4 simulations using Importance Biasing

Birgit Zatschler[a,*] **on behalf of the SuperCDMS collaboration**

[a] *Department of Physics, University of Toronto, Toronto, ON M5S 1A7, Canada*

E-mail: birgit.zatschler@utoronto.ca

SuperCDMS is a direct detection dark matter (DM) experiment currently being constructed at the SNOLAB underground laboratory in Sudbury, Canada. A complementary approach of cryogenically cooled Ge and Si crystals together with different sensor designs enables a broadband DM search for particles with masses $\leq 10\,\mathrm{GeV}/c^2$.

In order to reach this sensitivity, it is crucial to understand the background composition of the measured energy spectra. For this purpose, GEANT4 based simulations are performed in which all detector, cryostat, shielding and structural components are contaminated according to their known radioactive impurities from screening measurements. The subsequent decays and particle emissions are propagated through the setup and can create energy deposits in the sensitive Ge and Si crystals. Simulations for components located far away from the detectors are very inefficient and even with an extremely high number of primary events on the order of 10^{12} the detected energy spectra are lacking in statistics which propagates into non-negligible uncertainties in the background composition.

GEANT4 offers a mechanism called importance biasing which can increase the amount of detector hits by orders of magnitude for the same number of primary events. The challenges of implementing importance biasing in SuperCDMS' GEANT4 application and the achieved efficiency boost of the respective background simulations will be discussed in this article.

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[*] Speaker

1. Introduction

SuperCDMS' background simulation campaign includes the propagation of particles through a 20 cm thick gamma lead shield. In order to improve the efficiency of the simulations and increase the statistics of the recorded detector hits, importance biasing will be used for gamma-rays traversing this lead shield.

2. GEANT4's Importance Biasing

GEANT4 provides several Event Biasing Techniques [1–4]. SuperCDMS' implementation makes use of *modular physics list* which is based on the example *biasing/B02* provided with the GEANT4 software package [5]. Only one particle type is being affected by importance biasing at a time; in this case gamma-rays are biased.

2.1 Basic working principle

Fig. 1 shows a schematic of the working principle of importance biasing. It introduces importance layers which are virtual geometries overlaid on the lead shield geometry in the real world. Each importance layer L has assigned an importance value V, increasing from outside to inside with $V = 2^{L-1}$. Each time a gamma-ray crosses the boundary between two importance layers, where the importance value ratio between the next and the previous layer is 2, the particle is duplicated, i.e., copied. The copy has the exact same properties as the original particle, i.e., the same energy, momentum direction, position, etc. Additionally, the track weight of both particles is divided by 2. Both particles can then continue their path independently of each other, i.e., the next physics process is determined individually for each particle.

In the other direction, when a gamma-ray crosses the boundary between two importance layers and the ratio between the next and the previous layer is 1/2, there is a 50% probability that the particle track is killed. In the case the particle survives, its track weight is doubled.

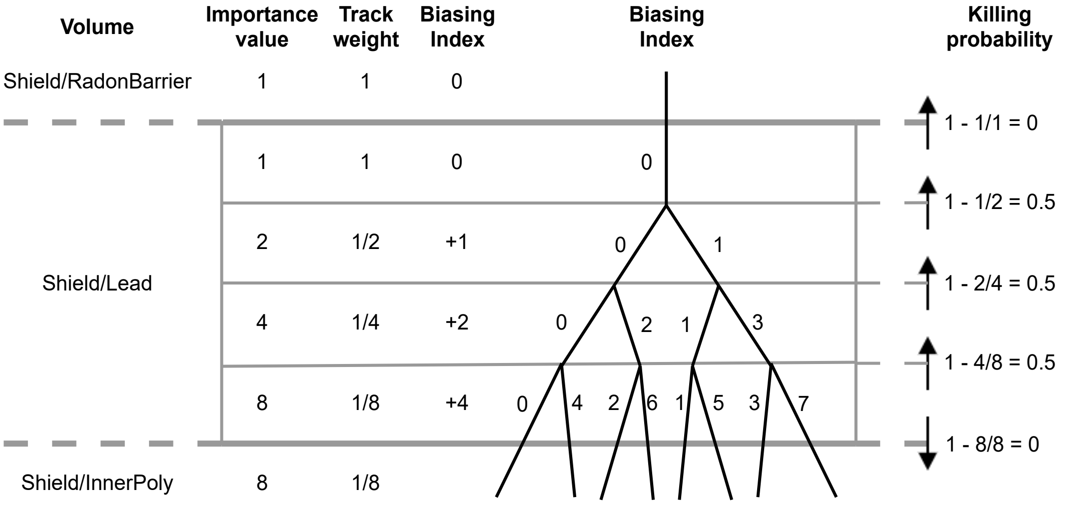

Figure 1: Overview of the basic working principle of importance biasing with an example of 4 importance layers overlapping with the lead shield. The biasing index distinguishes the different track topologies.

These biasing techniques, i.e., duplicating and killing particles at importance layer boundaries, lead to more particles being tracked which are going into the direction of the detectors and fewer particles being tracked which are moving away from the detectors.

Fig. 1 also indicates that for the example of $L = 4$ importance layers, there are up to $2^{L-1} = 8$ different track topologies and you need to be able to distinguish between them to create a valid detected spectrum. If this is not done, one could observe more energy in the detector than what has been originally emitted.

2.2 Biasing Index

In order to distinguish between different track topologies and combine the detector hits of tracks that belong to the same topology, we introduce the biasing index $\mathcal{B}$. Fig. 1 shows the basic principle how the biasing index is calculated and propagated.

The primary particle starts with a biasing index of 0. Each time a particle is copied, the original particle keeps its biasing index, while the copied particle receives a new one. The biasing index $\mathcal{B}_{\text{copy}}$ of the copied particle is calculated by taking into account the original particle's biasing index and the importance value V of the importance layer into which the original particle has just moved: $\mathcal{B}_{\text{copy}} = \mathcal{B}_{\text{original}} + V/2$. Tracks with identical biasing indices within the same Geant4 event are combined to determine the total energy deposit of the event topology, while tracks with different biasing indices within the same Geant4 event can still be distinguished. Tracks generated from different primaries within the same Geant4 event are combined if their biasing indices are identical.

2.3 Validation studies

In order to validate that the importance biasing together with the biasing index is working as intended, simulations were performed with and without importance biasing and compared to each other. For this, primary particles are started at the radon barrier (see fig. 1) and are propagated through the importance layers overlaid on the lead shield. After the innermost importance layer, i.e., at the inner polyethylene shield, the particle tracks, their energy and track weight are recorded and the resulting spectra are constructed taking into account the biasing index. See the corresponding presentation at the TAUP 2023 conference for example spectra [6]. This comparison has been done for each isotope and decay chain that are supposed to be simulated to model SuperCDMS' background.

2.4 Efficiency Boost

Depending on the importance layer thickness and the number of layers, importance biasing can introduce a significant efficiency boost when compared to an unbiased simulation. The efficiency boost is calculated by looking at how many different biasing indices $N_{\mathcal{B},i}$ are recorded for each event i on average:

$$\overline{N_{\mathcal{B}}} = \frac{\sum_i N_{\mathcal{B},i}}{N_{\text{primaries}}} \tag{1}$$

In the unbiased simulation, $N_{\mathcal{B},i}$ will always be 1, while in the biased simulation it can be much larger. The efficiency boost ε is then calculated by:

$$\varepsilon = \frac{\overline{N_{\mathcal{B},\text{ biased}}}}{\overline{N_{\mathcal{B},\text{ unbiased}}}} \tag{2}$$

This efficiency boost does not take into account the runtime of the simulations. Since the biased simulation has to propagate significantly more tracks, it runs longer than the unbiased simulation. Hence, the efficiency boost should be normalized by the runtime and the number of simulated primaries $N_{\text{primaries}}$:

$$\varepsilon_{\text{normalized}} = \varepsilon \cdot \frac{t_{\text{unbiased}}}{t_{\text{biased}}} \cdot \frac{N_{\text{primaries, biased}}}{N_{\text{primaries, unbiased}}} \tag{3}$$

Table 1 contains a few examples of different primary particles and isotopes started at the radon barrier as described above. The efficiency boost has been determined for 16 importance layers each having a thickness of 1.25 cm, thus covering the full 20 cm lead shield.

Table 1: Examples of the efficiency boost with and without taking into account the longer runtimes for the biased simulation. Note that for ^{232}Th the full decay chain has been simulated without producing neutrons.

Primary	ε	$\varepsilon_{\text{normalized}}$
2 MeV γ	33454	1023
^{40}K	28177	22697
^{232}Th	33708	17173

3. Conclusion

GEANT4's importance biasing is a powerful tool which can increase the simulation efficiency on the order of several magnitudes. It allows a substantial reduction of the simulation runtime by generating considerably fewer primaries, while at the same time significantly increasing the number of detector hits per simulation job. Thus, SuperCDMS' future background simulations will provide sufficient statistics for studying the background contribution of components far away from the detectors. Also, statistics required to develop a proper background model can finally be achieved. On a final note, GEANT4's importance biasing makes it possible to reduce our carbon footprint by needing less computing time to meet our objectives.

References

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