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Author(s):
Armstrong, Hirotatsu
James, Michael R.
McKinney, Gregg W.

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Delayed Neutron and Photon Energy Biasing in MCNP6

H. Armstrong[1, 2], M. R. James[2], G. W. McKinney[2]

[1]*The University of Texas at Austin, 1 University Station C2200, Austin, TX 78712*
[2]*Los Alamos National Laboratory, MS-E540, Los Alamos, NM 87545*
armstrhu@utexas.edu, mrjames@lanl.gov, gwm@lanl.gov

INTRODUCTION

Delayed particles (photons and neutrons) are important in many applications such as active interrogation for detection of special nuclear materials (SNM). With active interrogation, the presence of a delayed signal after the initial interrogation event is a strong indicator to the presence of fissionable material [1][2]. Biasing the delayed particle production is an important variance reduction application as the number of delayed particles created is typically small compared to the number of histories run. Several techniques in the current version of MCNPX (2.70) [3] allow for biasing of the delayed particles as a form of variance reduction to obtain more statistically significant tallies. Delayed neutron biasing (ACT card with DNBIAS=1-10) allows for the user to bias the number of delayed neutrons created per fission event. The SPABI card allows for additional biasing as it splits designated secondary particles based on the energy at which they are born. Combining these biasing techniques with others such as cell importances allows the user to reduce the variance of the contribution to a tally from delayed photons and neutrons.

Biasing the number of delayed particles in some energy region can be accomplished with the variance reduction techniques given above; however, for certain scenarios those methods of energy biasing of delayed particles may not be adequate. Take for example a hypothetical isotope which emits a 5keV delayed gamma 99.9999% of the time, and a 1.2MeV delayed gamma 0.0001% of the time. In this case, every 10^6 histories results in only a single 1.2 MeV gamma created (on average). The user typically will not want to transport many 5keV photons as they are usually inconsequential to the solution they are after. Splitting the 1.2 MeV photon 10 to 1 with the SPABI card results in 10 gammas at 1.2 MeV, at 1/10th the weight, per 10^6 particles. However, having just 10 1.2 MeV photon histories per 10^6 particles does not greatly improve the sampling efficiency in the high energy region. Using the CUT card to kill the 5keV photons could be an option; but even with this MCNPX would still spend time sampling 999,999 5keV photons only to then kill them. This excessive amount of wasted sampling is computationally inefficient. Rouletting particles based on energy would have the same issues.

The new delayed neutron and photon energy biasing allows for the user to specify energy bins and relative importances in those energy bins. The delayed particles will then be sampled from the user supplied distribution with appropriate weight adjustments such that a fair game is maintained. Using this technique, the user could place an energy bin with a high importance around the 1.2MeV gamma and place low importance on the region encompassing the 5keV gamma. Even a modest uniform importance over all energies will lead to 500,000 unique histories for each of the 5keV and 1.2MeV photons per 10^6 histories run.

METHODOLOGY

The implementation of this energy biasing requires the user to specify energy bins and importance's over all energies from $[0,E_{max}]$ where E_{max} is the maximum energy of the problem for the delayed particle type being biased, and is specified on the PHYS card for that particle type (photons or neutrons). The user specified energy importances are normalized and now represent the sampling probability (PDF) of the delayed particles in each of the energy bins. The probabilities are converted into a CDF and the delayed particles are sampled from this distribution.

To maintain an unbiased solution, the weights of the particles must be adjusted appropriately for each of the delayed particles that are sampled. This is accomplished by multiplying the particles current weight by the ratio of the true sampling probability to the biased sampling probability. The implementation of this is slightly more complicated due to where the user specified energy bins fall in relation to the true sampling distribution energy bins.

Table I. Sample Energy Biasing Scheme (E_1-E_5)

<table>
<tr><td colspan="2">e_1</td><td colspan="2">e_2</td><td>e_3</td><td>e_4</td><td colspan="2">e_5</td><td>e_6</td></tr>
<tr><td colspan="2">1/10</td><td colspan="2">1/10</td><td>3/10</td><td>0/10</td><td colspan="2">2/10</td><td>3/10</td></tr>
<tr><td>E_1</td><td colspan="2">E_2</td><td colspan="2">E_3</td><td colspan="2">E_4</td><td colspan="2">E_5</td></tr>
<tr><td>1/10</td><td colspan="2">2/10</td><td colspan="2">3/10</td><td colspan="2">2/10</td><td colspan="2">2/10</td></tr>
<tr><td>w_1</td><td>w_2</td><td>w_3</td><td>w_4</td><td>w_5</td><td>w_6</td><td>w_7</td><td>w_8</td><td>w_9</td></tr>
</table>

To illustrate the weight adjustment algorithm, Table 1 gives a hypothetical situation where delayed particles are emitted into 6 energy groups (e_1-e_6) with some probability distribution. The user specifies upper energy bin values for energy biasing (E_1-E_5) as well as relative importances. In this scenario, there are 9 possible weight adjustment parameters (w_1-w_9) for each of the energy regions in which a sampled particle can reside. The reason there are 9 regions rather than 5 (biased sampling distribution) or 6 (true sampling distribution) is due to different probabilities of falling into those regions given uniform sampling in any energy bin. For instance, if the user specified distribution is sampled, then the probability of falling into energy bin E_1 is 0.1. However, the true probability of falling into the range $(0,E_1)$ is not 0.1 from the true PDF. Rather it is $0.1 \cdot \left(\frac{E_1}{e_1}\right)$, or the true probability multiplied by the width of the sampled energy bin to the true energy bin. Similarly, the probability of selecting and energy between (E_1,E_2) is 0.2; but if the energy sampled happens to be below e_1, the probability of falling into (E_1,e_1) within (E_1,E_2) is not 0.2 but rather $0.2 \cdot \frac{(e_1-E_1)}{(E_2-E_1)}$. The true sampling probability is given by $0.1 \cdot \frac{(e_1-E_1)}{e_1}$. In this case, taking the ratio of the two to obtain the weight adjustment factor w_2 gives

$$w_2 = \frac{0.1 \cdot (E_2 - E_1)}{0.2 \cdot e_1}. \tag{1}$$

In general, if the sampled energy falls into bin *i* of the biased distribution and bin *j* of the true distribution, then the weight adjustment parameter for that energy is given by

$$w = \frac{P_j \cdot (E_i - E_{i-1})}{B_i \cdot (e_j - e_{j-1})}, \tag{2}$$

where P_j is the true sampling probability in energy bin *j* and B_i is the biased sampling probability in energy bin *i*.

Since the user will not generally know the true energy distribution of delayed particles, it is likely that the user defined energy biasing bins will specify a sampling probability over an energy range where there is zero probability of emission in the true distribution. Because of this, user supplied biasing distribution is zeroed out in these energy regions and renormalized to prevent the creation of delayed particles in those energy regions that are not allowed. Sampling this new biasing distribution prevents the production of delayed particles in unpermitted energy regions and preserves an overall unbiased solution.

RESULTS

The results of implementing the delayed particle energy biasing for photons using multigroup data (ACT card with DG=mg) are presented. Figure 1 plots the ratio of F1 tally results using the biasing technique to the unbiased tally results over 256 linearly spaced bins from 0-7.5MeV. The ratio shows small random fluctuations about 1.0 over the range from 0 to about 6MeV; above this the tallies have not fully convergence which leads to the large fluctuations in the ratio above 6MeV. Figure 1 shows how the results obtained using energy biasing converges to the true solution and no systematic biasing is introduced by using delayed particle energy biasing.

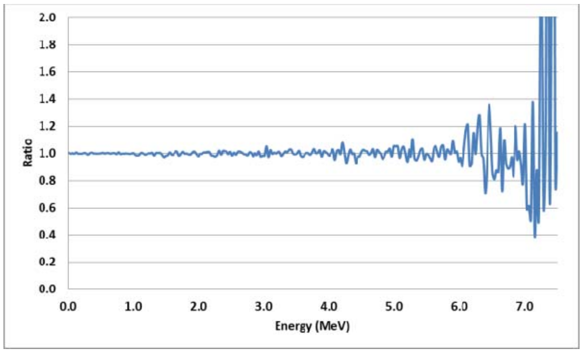

Figure 1. Ratios of F1tally results between unbiased and energy biased delayed particles. The small fluctuations about 1.0 show proper convergence of the technique.

Figure 2 compares F1 tally results for 10^4 histories where an energy biasing bin of high importance has been placed between 1MeV and 2MeV. This preferentially samples delayed photons in the energy range 1-2MeV at the expense of sampling delayed photons over all other energies to reduce the variance in the region of interest. Although not plotted, the relative errors in the other energy regions (0-1MeV and 2MeV-E_{max}) are large enough such that the values are numerically equivalent to the unbiased distribution. Running more particle histories such that the energies outside the region of interest have more samples will result in a solution that converges to the unbiased case. The actual amount of improvement in the statistics is dependent upon the biased probabilities provided as well as the true sampling probabilities. Since the user will not typically know the true sampling distribution, the actual reduction in the variance cannot be easily estimated by the user.

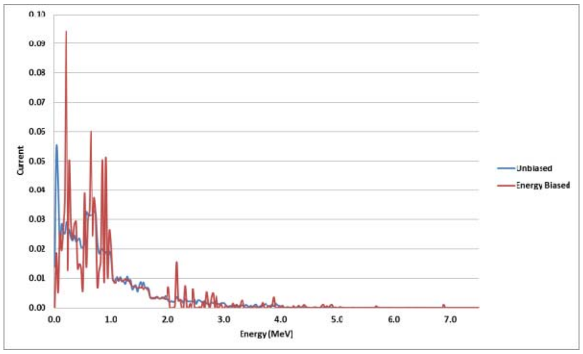

Figure 2. Delayed photon energy biasing implementation with a biasing bin placed between 1 and 2MeV. The variance in this region is reduced compared to the unbiased tally, at the expense of increased variance at other energies.

Delayed particle energy biasing can also be used to investigate the contribution to a tally (ex. dose) by various components of the delayed spectrum. This can be accomplished using biasing bins of zero importance. Placing a zero importance bin over an energy region will prevent sampling of delayed particles over that energy region.

The time integrated photon spectrum from 0.1MeV neutrons incident on ^{59}Co is given in figure 3. The two peaks at 1.17MeV and 1.33MeV are from the decay of ^{60}Co which is created when ^{59}Co absorbs a neutron. If time bins are used, the only photons emitted after the initial interaction between the neutron and ^{59}Co are the two peaks from the decay of ^{60}Co.

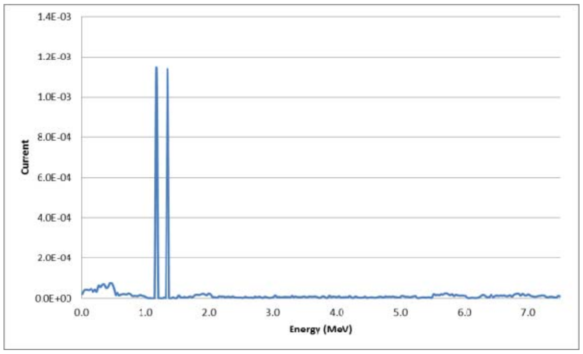

Figure 3. Time integrated photon spectrum from 0.1MeV neutrons incident on ^{59}Co. The peaks at 1.17MeV and 1.33MeV are from the decay of ^{60}Co.

Investigation of the contribution of either of the peaks to a tally can be done by specifying biasing bin boundaries about each of the two energy peaks, and placing zero importance over the peak which is to be removed. Figure 4 shows the removal of the 1.17 MeV ^{60}Co peak by using this technique.

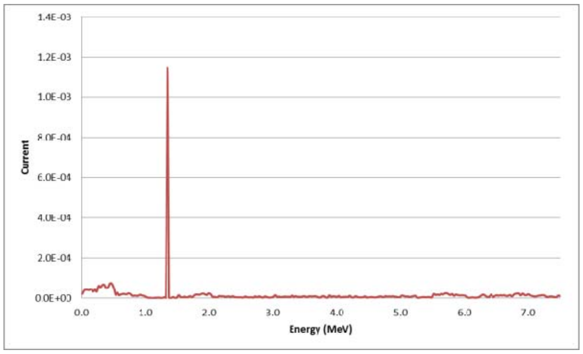

Figure 4. A zero importance energy biasing bin placed around the 1.17MeV peak removes the peak from the spectrum. All other energies are unaffected.

CONCLUSIONS

Delayed particle energy biasing is a variance reduction technique that changes the underlying distribution to preferentially sample particles in energy regions of interest. The technique is most useful in cases where the energy region of interest has a very low sampling probability in the true distribution. In these cases, other variance reduction techniques that involve splitting particles that have already been sampled will not lead to a large increase in the number of delayed particles in the energy ranges of interest. Only by modifying the underlying sampling distribution is it possible to significantly increase the probability of sampling a particle over that particular energy range.

When using delayed particle energy biasing, the user should be aware that because the true sampling probabilities are not usually known, there may be situations where specifying an energy biasing bin will increase the variance in the region where the user wants the variance reduced. This can occur when the user places a bias sampling probability of say 0.5 over a region that that has a higher true sampling probability, say 0.6. In this case, the variance in the region of interest will increase; however, since total probability must be conserved, this will be offset by a decrease in the variance in some other energy region.

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