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Delayed Neutron and Photon Energy Biasing in MCNP6

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INTRODUCTION

The production of delayed particles in MCNP6 [1] allows for modeling of many scenarios such as determining an accurate k_{eff} value for a reactor that is prompt subcritical. Delayed photons and neutrons can also be used in homeland security applications. The delayed gamma signature can be looked for to identify the material or the characteristic die-away of the delayed neutron signal can be analyzed for the same purpose.

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] 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. The SPABI card allows for additional biasing as it splits designated secondary particles based on the energy at which they are born. Combining these variance reduction 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, for every 10^6 histories run there would only be a single 1.2MeV 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 1.2MeV photon 10 to 1 with the SPABI card still only leads to 10 histories per 10^6 particles run. Even those 10 histories are not completely independent as each will start with the same energy, location, and direction; only the fate of the particles after creation will be different. Using the CUT card to kill the 5keV photons could be an option; but even with this MCNP would still spend time sampling 999,999 5keV photons only to then kill them; rouletting 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 and is specified on the PHYS card. 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 fall into. 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

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

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

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

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

RESULTS

Results of the implementation of delayed particle energy biasing for photons using multigroup data (ACT card with DG=mg) is presented below. 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.

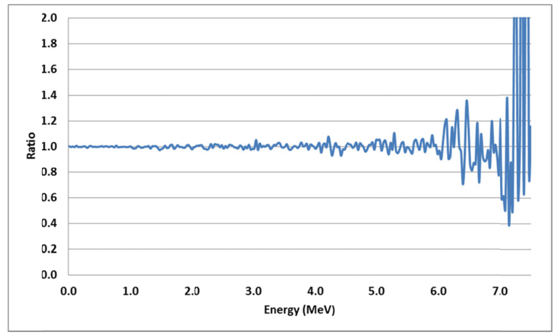

Figure 1. Ratios of F1tally results between unbiased and energy biased delayed particles. The small fluctuations about 1.0 show proper convergence of the technique.

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. 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.

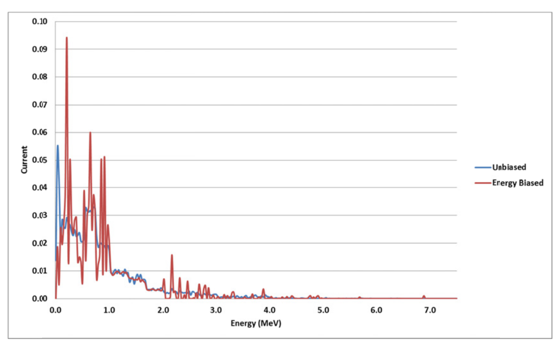

Figure 2. Delayed photon energy biasing implementation with a biasing bin placed between 1 and 2MeV. The variance in this region is reduced compared to the unbiased tally, at the expense of increased variance at other energies.

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 true distribution has a very low probability of sampling a delayed particle in the energy regions of interest. In this case, other variance reduction techniques that involve increasing the number of particles created or splitting those 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 in some particular energy range.

When implementing delayed particle energy biasing the user should be aware that since the true sampling probabilities are not usually known, there may be situations where specifying the energy biasing bin will increase the variance in the region where the user wanted 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.

REFERENCES

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