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Coupling External Radiation Transport Code Results to the GADRAS Detector Response Function

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Abstract

Simulating gamma spectra is useful for analyzing special nuclear materials. Gamma spectra are influenced not only by the source and the detector, but also by the external, and potentially complex scattering environment. The scattering environment can make accurate representations of gamma spectra difficult to obtain. By coupling the Monte Carlo Nuclear Particle (MCNP) code with the Gamma Detector Response and Analysis Software (GADRAS) detector response function, gamma spectrum simulations can be computed with a high degree of fidelity even in the presence of a complex scattering environment. Traditionally, GADRAS represents the external scattering environment with empirically derived scattering parameters. By modeling the external scattering environment in MCNP and using the results as input for the GADRAS detector response function, gamma spectra can be obtained with a high degree of fidelity. This method was verified with experimental data obtained in an environment with a significant amount of scattering material. The experiment used both gamma-emitting sources and moderated and bare neutron-emitting sources. The sources were modeled using GADRAS and MCNP in the presence of the external scattering environment, producing accurate representations of the experimental data.

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INTRODUCTION

The Gamma Detector Response and Analysis Software (GADRAS) developed by Sandia National Laboratories predicts the response of a gamma-ray detector in the presence of radioactive material [1, 2]. The specific response of the detector to a given radioactive source depends on the external scattering environment. Traditionally, GADRAS has used several empirical scatter parameters to simulate the general scattering environment. Some radiation transport codes, such as the Monte Carlo Nuclear Particle (MCNP) code [3] developed by Los Alamos National Laboratory, model the external scattering environment directly and tally radiation currents on multiple surfaces. By using the radiation transport code to model the radiation current on multiple facets of a detector in a given scattering environment, GADRAS can compute gamma-ray spectra and neutron count rates for a given scenario with a higher degree of fidelity than can be obtained by applying default scatter parameters. This study uses MCNP to model several different sources in a complex scattering environment to compute the gamma and neutron currents over multiple surfaces of a detector. GADRAS computes the detector response from these surface currents to generate a gamma-ray spectrum. These computations are then compared with experimental data. Previous work by Rawool-Sullivan et al. combined MCNP and GADRAS to simulate HPGe gamma spectra [4]. Their work involved modeling 3-dimensional sources in MCNP to calculate the neutron and gamma leakage from the source. This calculated leakage was then used to collapse the 3-dimensional source to a 1-dimensional source term that could be analyzed with GADRAS. The research done for this current project builds upon Rawool-Sullivan's work and further enhances the capabilities of coupling GADRAS with radiation transport codes.

MULTI-FACETED DATA IN GADRAS

GADRAS supports multi-faceted data by accepting separate current densities for the front, sides, and back of a detector. An external radiation-transport code, such as MCNP, simulates the external scattering environment and tallies the energy-dependent current on each surface of the modeled detector. When GADRAS processes multi-faceted files, it is assumed that the external scattering radiation has already been taken into account by the external radiation-transport code. Therefore, it only adds radiation that scatters within the detector housing (or whatever configuration applies when the detector is characterized). Because interactions occurring outside the detector housing are not taken into account the radiation-transport code must tally photons and neutrons that scatter into the detector from the floor, walls, ceiling, and any other object in the detector's vicinity. Shielding on the sides and/or back of the detector is taken into account during the detector characterization, so these features should not be modeled by the external radiation-transport code. Although GADRAS is able to predict the contribution of externally scattered radiation to the detector response, the external scatter calculations in GADRAS should be suppressed to use the multi-faceted data generated by the external radiation-transport code correctly. Users can suppress GADRAS' externally scattered radiation contribution by setting all of the scatter parameters to zero. If experiments are performed with varying source-to-detector distances, then multiple radiation transport calculations should be performed to tally the currents at the new locations.

MCNP METHODOLOGY

To compute the detector surface currents for a given scenario, the MCNP model should contain a cylindrical volume representing the detector. The cylinder should be positioned at the detector location with dimensions similar to those of the detector. The current tally (F1) should be used to tally the photons and neutrons that cross each individual surface. The pulse-height tally (F8) is not appropriate for use with GADRAS, as this tally represents the detector response function generated by MCNP and cannot be readily converted to a format that is usable with GADRAS. The current tally should be generated with the energy bin structure provided with the GADRAS distribution in the "MCNPbins.dat" file. (Note: energies given in MCNPbins.dat are in keV and must be converted to MeV for usage in MCNP.) A simple example in Figure 1, below, shows a Cs-137 source 1 meter away in air. A photon importance of zero in the detector cell ensures that the flux tally does not double-count particles that pass through the detector volume.

```
Simple Example Input Deck
1 0 -1 imp:p=0 $ detector volume
2 1 -0.0012 -2 1 imp:p=1 $ surrounding air
3 0 2 imp:p=0

1 rcc 100 0 0  10 0 0  10 $ detector surfaces
2 so 1000 $ universe sphere

mode p
sdef par=p pos=0 0 0 erg=0.6617
m1   7014 -75 $ air
     8016 -25
f1:p 1.1  $ side of cylinder, side of detector
f11:p 1.2 $ bottom of cylinder, front face of detector
f21:p 1.3 $ top of cylinder, back face of detector
e0 {insert values from MCNPbins.dat}
```

Figure 1. A simple MCNP input deck used with the multi-faceted GAM files in GADRAS.

The "outp" or "mctal" files should be used to calculate the current density on each respective detector face. GADRAS uses units of particles / (m^2s) to compute the detector response from multi-faceted GAM files. To convert the MCNP generated output to these units, the output values must be first multiplied by the source activity, and then divided by the respective surface area (in square meters) of the surface that represents the detector facet. For example, if a 1 uCi Cs-137 source is counted with a cylindrical detector with a radius of 10 cm and a length of 10 cm, the pseudo-code for scaling the currents would be:

$$\{\text{front current density}\} = \left\{\frac{\textit{front current}}{\textit{source particle}}\right\} * \frac{(1\times10^{-6}\ Ci)\left(3.7\times10^{10}\frac{Bq}{Ci}\right)\left(1\ \frac{1/s}{Bq}\right)}{\pi\,(10\ cm)^2\left(\frac{1\ m}{100\ cm}\right)^2}$$

$$\{\text{side current density}\} = \left\{\frac{\textit{side current}}{\textit{source particle}}\right\} * \frac{(1\times10^{-6}\ Ci)\left(3.7\times10^{10}\frac{Bq}{Ci}\right)\left(1\ \frac{1/s}{Bq}\right)}{2\pi\,(10\ cm)(10\ cm)\left(\frac{1\ m}{100\ cm}\right)^2}$$

$$\{\text{back current density}\} = \left\{\frac{\textit{back current}}{\textit{source particle}}\right\} * \frac{(1\times10^{-6}\ Ci)\left(3.7\times10^{10}\frac{Bq}{Ci}\right)\left(1\ \frac{1/s}{Bq}\right)}{\pi\,(10\ cm)^2\left(\frac{1\ m}{100\ cm}\right)^2}$$

Figure 2. Pseudo-code for scaling MCNP surface current outputs to units suitable for use with GADRAS.

After converting to the proper units, the current densities can be incorporated into the GADRAS multi-faceted GAM file.

GADRAS MULTI-FACETED GAM FILES

GADRAS computes gamma-ray spectra and neutron count rates by processing radiation data files. These files, termed GAM files, have different formats depending on how the data is represented in the GAM file. Figure 3 presents an example of a multi-faceted GAM file that contains current densities on each of the three detector faces. The second number of the first line represents format specification (the value 5 signifies that the GAM file format corresponds to multi-faceted current data). The second line lists 0 discrete gamma rays, 1,476 photon groups, and 78 neutron groups. Each line of the gamma-ray data lists four values: 1) the energy (keV) at the lower edge of the energy groups (*Note: MCNP outputs current with the energy bin at the higher edge of the energy groups*); 2) the current density (photons/s/m^2) incident on the front surface; 3) the average current density incident on the sides of the detector; and 4) the current density incident on the back surface. GADRAS represents detectors as if they are symmetric normal to the detector axis, so there is no distinction between the top, bottom, left, and right sides. Therefore, the average current over all the lateral sides of the detector should be specified as the third parameter on each line.

The neutron data also lists the current density on the front, sides, and back of the detector. The first column of the neutron lines is the energy of the neutron in eV at the lower edge of the energy group. The file contains NG+1 lines for the photon groups and NN+1 lines for the neutron groups, where NG is the number of photon groups and NN is the number of neutron groups. The leakage values are specified in units of inbound current density (particles/s/m^2, current divided by surface area) on each of the detector surfaces, not flux. When GADRAS computes the response function for a given detector, the surface area of each detector facet is taken into account. Therefore, the same GAM file can be used to compute the response of different detectors if they are situated at the same distance and height with respect to a radiation source.

```
0 5 ! NewFormat,ModelGeometry
0 1475 78 ! PhotonLines, PhotonGroups, NeutronGroups
2.000E+02   3.952E+04   4.155E+01   1.063E+02  ! photon groups
2.935E+02   1.222E+01   2.138E+00   7.240E-01
2.957E+02   2.742E-01   1.290E-01   2.181E-01
…
1.179E+04   0.000E+00   0.000E+00   0.000E+00
1.200E+04   0.000E+00   0.000E+00   0.000E+00
1.965E+07   3.016E-01   7.831E-03   3.073E+00  ! neutron groups
1.733E+07   5.249E+01   4.618E+00   2.870E+01
…
5.000E-03   4.727E-02   2.706E-06   0.000E+00
2.000E-03   1.149E-03   9.549E-08   0.000E+00
5.000E-04   4.277E+04   0.000E+00   9.003E+03
1.000E-05   0.000E+00   0.000E+00   0.000E+00
```

Figure 3. Multi-faceted GAM file example.

COMPARISON WITH EXPERIMENTAL DATA

For comparison, data was collected at the Device Assembly Facility at the Nevada National Security Site using a High Purity Germanium (HPGe) detector with a relative efficiency of 150% [5]. An MCNP model was created, which took the walls, floor, and ceiling of the room into account, as well other significant scattering materials such as iron tables, neutron detectors, neutron detector housing, and electronics modules. The source and detector, separated by 200 cm, were located 100 cm above the ground. The MCNP model was run for four different gamma-ray calibration sources, a moderated and unmoderated Cf-252 source, and the BeRPBall in both a moderated and an unmoderated configuration. The gamma-ray sources used in the experiment were Cs-137, Ba-133, Co-60, and U-232. Figure 4 and Figure 5 compare measurements (shown in black) with computed spectra (in red) that are derived by processing multi-faceted GAM files. The scatter parameters in the detector response function are set to zero so that GADRAS suppresses its own computation of scattered radiation. Figure 6, a screen capture of the detector parameter edit form, shows the response parameters that were used to compute these spectra.

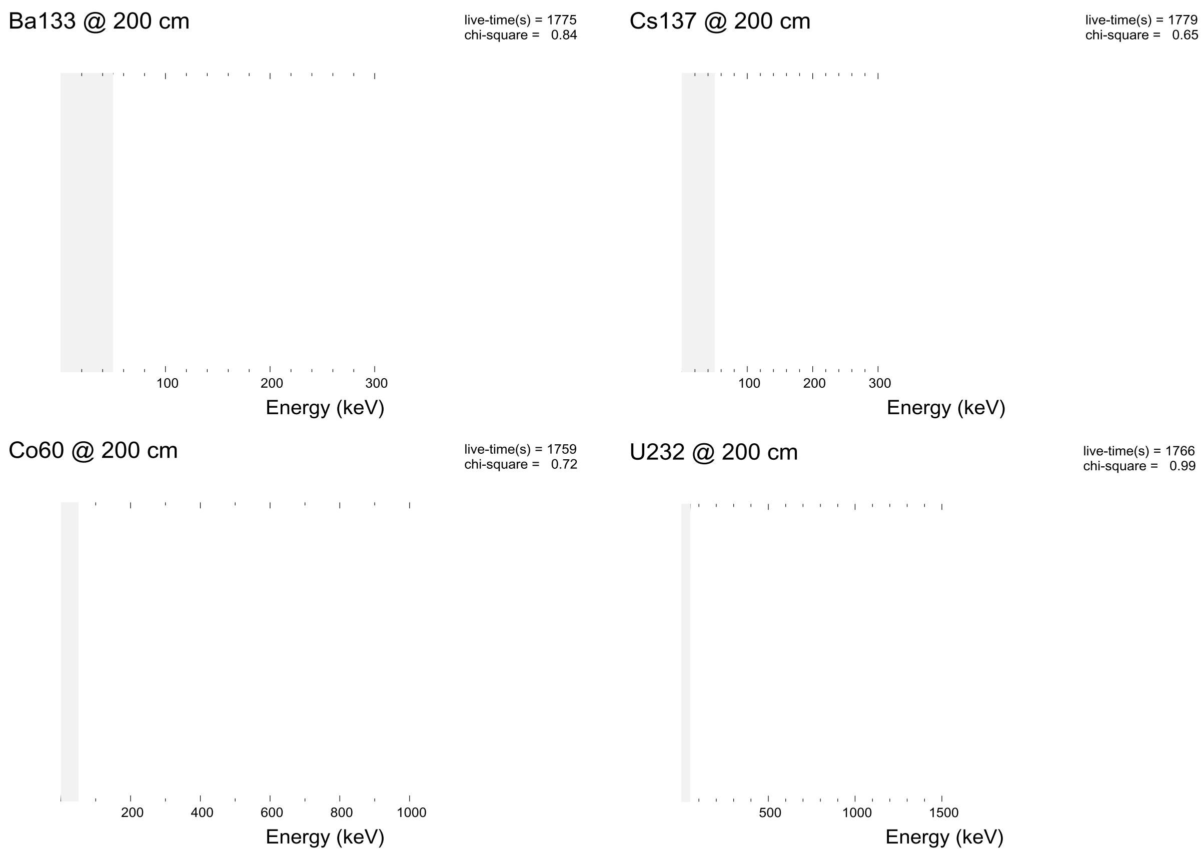

Figure 4. Measured spectra (*black*) compared with computed spectra for bare gamma-ray calibration sources (*red*) derived by processing multi-faceted GAM files.

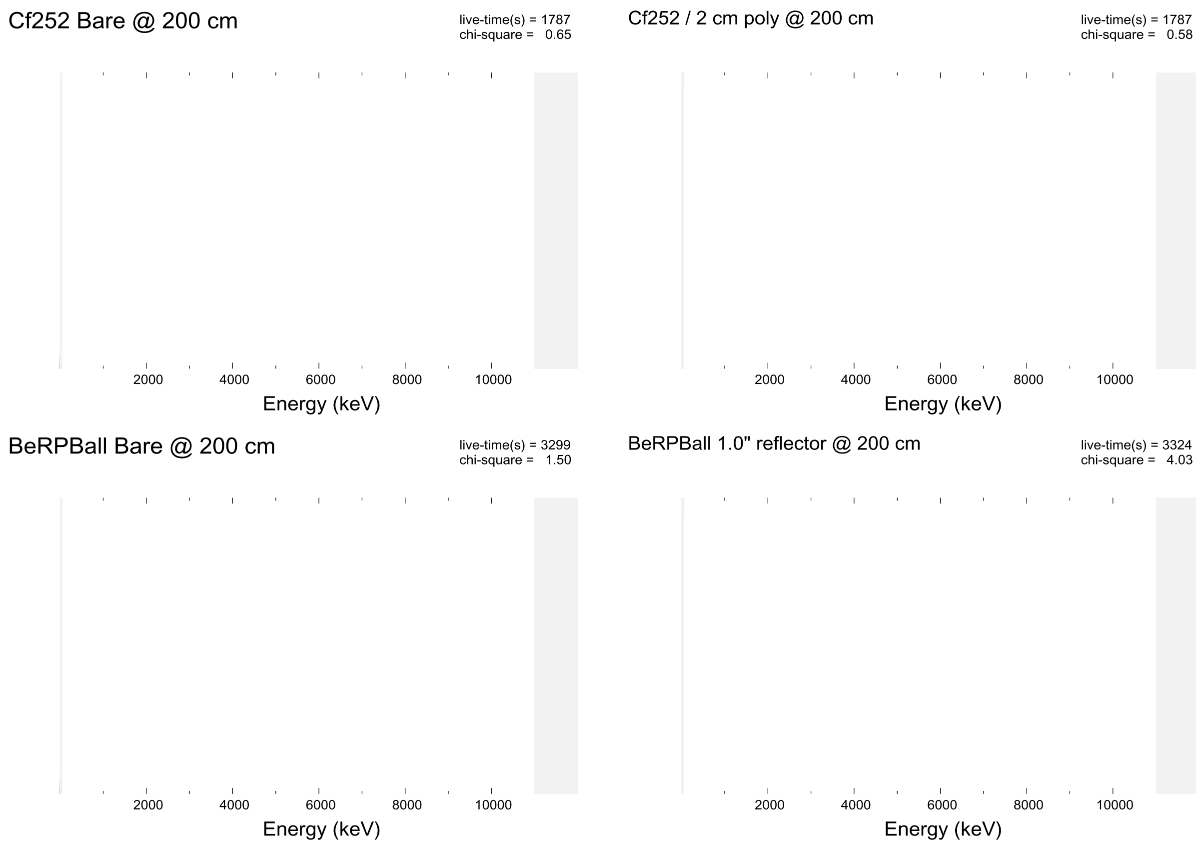

Figure 5. Measured spectra (*black*) compared with computed spectra for moderated and bare ^{252}Cf and BeRPBall sources (*red*) derived by processing a multi-faceted GAM file.

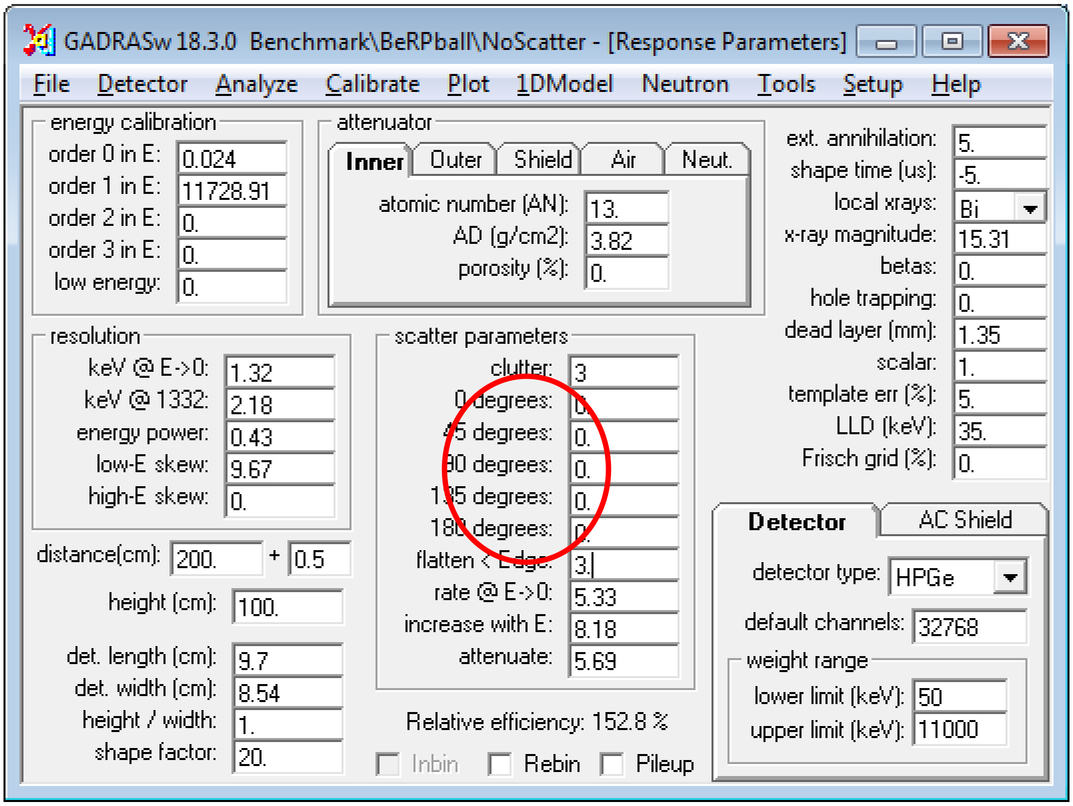

Figure 6. Detector edit form for response parameters used to compute spectra, identifying parameters ***(circled)*** **that affect the magnitude of scattered radiation.**

Figures Figure 4 and Figure 5 show that reasonably good agreement was obtained for each source, but small differences remain. Most of these differences can be attributed to statistical effects and can be eliminated with variance reduction or more particle histories. The spectra presented in this document and examples of multi-faceted GAM files being used to perform these calculations are installed with GADRAS in the "Benchmark\BeRPball\NoScatter" detector folder.

CONCLUSION

A new GADRAS feature now allows users to specify separate currents over multiple facets of a detector. These currents can be calculated by external radiation transport codes such as MCNP, allowing for accurate representation of complex environments. The detector response function is then calculated by GADRAS in these complex environments, thus improving the accuracy of the detector response function. Calculations for gamma and neutron sources in this work indicate that good agreement can be achieved when the GADRAS detector response function is applied to process multi-faceted input files that are produced by external radiation transport codes such as MCNP. Causes for minor differences between measured and computed spectra are being investigated. Future work will be performed to validate the accuracy of gamma and neutron sources in more complex scattering environments.

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