

# SaG4n

**Simulation of  $(\alpha, xn)$  reactions with Geant4**

**User's Manual**

**Release 1.4**

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## 0 Changes from the previous version

Release 1.4 of SaG4n includes the following changes with respect to release 1.3:

1. There is now the possibility of using the alphas of a given radioactive decay in the source, without having to write all the alpha energies and intensities in the input. For this, a database has been added in this release, in the new directory "data/AlphaSpectra". The database has been obtained mainly from the ENDF/B-VIII.0 decay data library. Details concerning how to use it are given in section 2.2.
2. A new keyword is introduced in the input file in order to provide the path to the mentioned database.
3. A new example with makes use of this database is provided in examples/fuel.
4. A new output histogram is provided by the code, "Source\_00", with the energy spectrum of the alpha particle source used in the calculation.

# 1 Introduction

## 1.1 Preamble

SaG4n is a Geant4 [1] tool developed to calculate neutron production due to nuclear reactions induced by  $\alpha$  particles in different materials. In its inception, it is thought for calculating the neutrons induced by the alphas naturally occurring in materials due to radioimpurities, but it is not restricted to that case.

Neutrons are a potential source of background for all rare-event searches, and are especially relevant for WIMP searches, where they are a source of irreducible background. The precision of the neutron yield is critical to evaluate the discovery potential of coming experiments and to reduce systematic effects in current data.

The code is available in <https://github.com/UIN-CIEMAT/SaG4n>. Once compiled with Geant4, SaG4n takes from an input file written by the user all the information necessary to define the geometry of the problem, the source, parameters of the physics, the type of output, etc... The program uses the electromagnetic models implemented in Geant4 to perform an explicit transport of the incident  $\alpha$  particles through the geometry, and data libraries originally written in ENDF-6 format to model the  $(\alpha, xn)$  reactions. The user is able to choose among the available data libraries (JENDL and TENDL, for instance, but also custom made ones). The computation time is reduced by the use of biasing techniques.

Its main features are that it is flexible in the selection of the data libraries to be used, it exploits the advantages of Geant4, it is transparent for the user to implement modifications as desired and it has is easily executed only by editing the mentioned input file.

In particular, the Geant4 capabilities most relevant for this use are three. First, it allows for almost arbitrarily complicated geometries. Second, it benefits from the electromagnetic processes already implemented for  $\alpha$  transportation. Third, it allows you to bias a particular process, in this case boosting the  $(\alpha, xn)$  cross section in order to reduce the computation time and make the simulation viable for this kind of studies. The amount of biasing and the level of detail in which the transport of the  $\alpha$  particles are carried out (via a maximum allowed step size) are controlled by the user. The code allows for the production of  $\gamma$ -rays as well, in coincidence or not depending on the information provided by the data libraries.

The output of the code is editable, but in its native version includes initial position and momentum of the generated  $\alpha$ , position and momentum of the produced neutron (and  $\gamma$  rays) and weight. The weight is given by Geant4 to each generated neutron to compensate the biasing that has been introduced to boost the  $(\alpha, xn)$  process in first place. The yield of neutrons per alpha can be calculated as

$$Y[n/\alpha] = \frac{1}{N_\alpha} \sum_{i=1}^{N_n} \omega_i$$

where  $N_n$  is the number of neutrons produced in the simulation,  $\omega_i$  the weight of each of them, and  $N_\alpha$  the number of simulated  $\alpha$  particles.

## 1.2 Usage

SaG4n is compiled in a similar way to any other Geant4 application. It is first necessary to have Geant4 installed. We recommend the compilation of SaG4n using CMake, with the creation of a build folder. The installation could be similar to the following:

```
$ tar -xzf SaG4n.01.00.tar.gz
$ cd SaG4n.01.00
$ mkdir build
$ cd build
$ source /home/you/geant4-install/share/Geant4-G4VERSION/geant4make/geant4make.sh
$ cmake -DGeant4_DIR=/home/you/geant4-install/lib64/Geant4-G4VERSION ../
$ make
```

After compiling the program, an executable named SaG4n should have been created inside the /build/ folder.

Before running the code, some environment variables must be set. They are the following:

```
$ source /home/you/geant4-install/share/Geant4-G4VERSION/geant4make/geant4make.sh
$ export G4PARTICLEHPDATA=/pathtoyourdatalibraries/ENDFLIBING4FORMAT
```

The environmental variable G4PARTICLEHPDATA must be pointing to the full path where is placed the ( $\alpha$ ,n) data library (JENDL/AN-2005, for example).

To run SaG4n, the name of the executable must be followed by the name of the corresponding input file. For example:

```
$ ./build/SaG4n inputs/examples/geometry/geom01.inp
```

The description of the input file is described in Section 0 and some examples distributed together with the code in Section 3.

## 2 Input description

The input is a text file containing all the information needed for the simulation.

The input file consists of a series of keywords followed by a variable amount of entries.

The “#” symbol is used to comment. Anything on a line that follows the “#” symbol is not read by the program.

The input file ends with the “**END**” keyword. Anything below this keyword is not read by the program.

Units: distances are in cm, densities in g/cm<sup>3</sup>, energies are in MeV.

The entries described below can be written in three types of formats, which are indicated in square brackets. These formats are integer numbers, real numbers, or character strings.

The list of keywords is the following:

Keyword	Description	Optional	Default value
<b>VOLUME</b>	To define the volumes of the geometry	no	
<b>MATERIAL</b>	To define the materials of the geometry	no	
<b>WORLDSize</b>	To define the total size of the geometry	yes	1000
<b>SOURCE</b>	To define the source	no	
<b>OUTPUTTYPE</b>	Controls the type of information appearing in the output file(s)	yes	1 0 2
<b>OUTPUTFILE</b>	Name of the output file	yes	./output
<b>MAXSTEPSIZE</b>	Maximum step size for the transport of the alpha particles	yes	0.001
<b>BIASFACTOR</b>	Biasing factor for the cross sections	yes	-1
<b>NEVENTS</b>	Number of histories to be run	yes	100 000
<b>SEED</b>	To set the seed for the random number generator of the Monte Carlo	yes	1234567
<b>INTERACTIVE</b>	If defined, Geant4 runs in interactive mode	yes	not in input
<b>DONOTKILLSECONDARIES</b>	If defined, secondary particles are transported	yes	not in input
<b>SAG4NDATABASEDIR</b>	Provides the path to the SaG4n database.	Yes	not in input
<b>END</b>	End of the input	no	

## 2.1 Geometry

The geometry of the problem is defined with the keywords: **VOLUME**, **MATERIAL** and **WORLDSize**.

The keyword **VOLUME** is used to define the volumes of the geometry. Up to 100 different volumes can be defined in the input. For the moment, three types of volumes can be defined: spheres, parallelepipeds (with the sides parallel to the XYZ axis) and cylinders (with the symmetry axis parallel to the Z axis). Each volume can be inserted either in the *world* volume or inside any of the other defined volumes. The world volume is the largest one, and it contains all the other volumes. In this program the world volume is defined by default and does not have to be explicitly defined in the input file. It consists of a 1000 cm side cube made of vacuum. The size of the cube side can be changed with the **WORLDSize** keyword with the following entry:

**WORLDSize** **WSize**

Where:

**WSize** [real] is the new size of the world cube side, in cm.

Each of the volumes should appear in the input with the following entries:

**VOLUME** **VolID** **VolName** **MatID** **VolType** **MotherID** **DummyWord**  $\lambda_1$   $\lambda_2$  ...  $\lambda_{N\lambda}$

Where each of the entries is:

**VolID** [integer] – Is the volume identification number. Any non-zero integer can be used for this entry. Each volume should have a different **VolID** number.

**VolName** [string] – Is the name of the volume. The output may use this field to give the results.

**MatID** [integer] – The identification number of the material from which the volume is made. Materials are defined with the **MATERIAL** keyword. Each material has a different identification number.

**VolType** [integer] – Defines the type of volume: sphere (**VolType** = 1), parallelepiped (**VolType** = 2) or cylinder (**VolType** = 3).

**MotherID** [integer] – Defines where the volume is inserted (the mother volume). To insert the volume into the world volume: **MotherID** = 0. To insert the volume inside any other volume, set the **MotherID** number to the **VolID** number of the desired mother volume.

**DummyWord** [string] – not used at this moment. It is used only to separate the  $\lambda_i$  entries from the rest.

$\lambda_1$   $\lambda_2$  ...  $\lambda_{N\lambda}$  [real] – parameters used to define the dimensions and position of the volume. The position of the volume is defined with a translation vector (vx,vy,vz) which corresponds to the translation of the volume with respect to its mother volume. The meaning of the  $\lambda$ -parameters depends on the volume type (all of them in cm):



**VolType** = 1 (Sphere - **Nλ**=4): **λ<sub>1</sub>** is the radius of the sphere (in cm); and vx=**λ<sub>2</sub>**, vy=**λ<sub>3</sub>**, vz= **λ<sub>4</sub>**. The center of the sphere is placed is (vx,vy,vz) with respect to its mother volume.

**VolType** = 2 (Parallelepiped parallel to the X, Y and Z axis - **Nλ**=6): **λ<sub>1</sub>** is the length of the side parallel to the X axis; **λ<sub>2</sub>** is the size of the side parallel to the Y axis; **λ<sub>3</sub>** is the size of the side parallel to the Z axis; and vx=**λ<sub>4</sub>**, vy=**λ<sub>5</sub>**, vz= **λ<sub>6</sub>**. The center of the parallelepiped is (vx,vy,vz) with respect to its mother volume.

**VolType** = 3 (Cylinder parallel to the Z axis - **Nλ**=5): **λ<sub>1</sub>** is the radius of the cylinder; **λ<sub>2</sub>** is the length of the cylinder; and vx=**λ<sub>3</sub>**, vy=**λ<sub>4</sub>**, vz= **λ<sub>5</sub>**. The center of the cylinder in (vx,vy,vz) with respect to its mother volume.

General note on the **λ** parameters: Note that full dimensions are used, instead of half-dimensions as usually done by Geant4.

#### Example:

```
VOLUME 5 Sphere01      10 1 0 --- 20 3 5 7
VOLUME 6 Box01         13 2 5 --- 3 3 3 0 0 0
```

These two lines in the input define two volumes: a sphere made of a material with MatID=10 (has to be defined in the input) and with 20 cm radius, centered in x=3 cm, y=5 cm and z=7 cm, and a 3x3x3 cm<sup>3</sup> parallelepiped centered in the center of the sphere, made of a material with MatID=6 (has to be defined in the input).

The materials are defined with the **MATERIAL** keyword. Up to 100 different materials can be defined in the input file. Each of them has an identification number, which is used to assign them to the volumes. There are two possibilities to define a material. They are the following:

**MATERIAL** MatID MatName Density Niso

**ZAID<sub>1</sub>** IsoFraction<sub>1</sub>

**ZAID<sub>2</sub>** IsoFraction<sub>2</sub>

...

**ZAID<sub>Niso</sub>** IsoFraction<sub>Niso</sub>

**ENDMATERIAL**

Where each of the entries is:

**MatID** [integer] – Material identification number. Any non-zero integer can be used for this entry.

**MatName** [string] – Name of the material.

**Density** [real] – Density of the material, in g/cm<sup>3</sup>.

**Niso** [integer] – Number of isotopes or elements from which the material is made.

**ZAID<sub>i</sub>** [integer] – Atomic number  $Z$  and mass number  $A$  of the isotope  $i$ , written as  $\text{ZAID} = 1000 \times Z + A$ . For example,  $^{56}\text{Fe}$  has  $\text{ZAID}=26056$ ; and  $^{235}\text{U}$  has  $\text{ZAID}=92235$ . Materials can also be defined from their elements. In this case **ZAID<sub>i</sub>**= $Z$ , i.e. the atomic number of the element has to be provided. Each material is defined either from its elements, or from its isotopic abundances. Elements and isotopes cannot appear both in the same material.

**IsoFraction<sub>i</sub>** [real] – If **ZAID<sub>i</sub>** is an isotope ( $1000 \times Z + A$ ), then **IsoFraction<sub>i</sub>** is the atomic fraction of the isotope  $i$ . If **ZAID<sub>i</sub>** is an element, then **IsoFraction<sub>i</sub>** can be either positive or negative. If positive, **IsoFraction<sub>i</sub>** is the atomic fraction of element  $i$ . If negative, **-IsoFraction<sub>i</sub>** is the mass fraction of element  $i$ . Negative and positive values cannot appear both in the same material. In any case, the values of **IsoFraction<sub>i</sub>** don't need to be normalized.

**ENDMATERIAL** – At the end of each material description, with **Nlso** pairs of **ZAID** and **IsoFraction** values, the word **ENDMATERIAL** should appear.

Alternatively, the materials can be defined using the Geant4 material database. This can be done in the following way:

**MATERIAL MatID G4MatName DummyFloat Nlso**

Where each of the entries is:

**MatID** [integer] – Material identification number. Any non-zero integer can be used for this entry.

**MatName** [string] – Name of the material as it appears in the Geant4 material database. Some examples are `G4_WATER`, `G4_AIR` ... The complete list can be found in the `G4NistMaterialBuilder` class or in the Geant4 manual. It can also be accessed via the UI command (running in interactive mode): `Idle> /material/nist/listMaterials all`

**DummyFloat** [real] – Any real number, which will not be used by the program.

**Nlso** [integer] – Any **negative** integer.

**Example:**

```
MATERIAL 9 H2O 1.00 5
1001 1.99977
1002 0.00023
8016 0.99757
8017 0.00038
8018 0.00205
ENDMATERIAL
```

These lines define a material, which is water with density  $1.00 \text{ g/cm}^3$ . The identification number is `MatID=9`. An equivalent definition is:

```

MATERIAL 9 H2O 1.00 2
1 2
8 1
ENDMATERIAL

```

And also:

```

MATERIAL 9 H2O 1.00 2
1 -11.19
8 -88.81
ENDMATERIAL

```

Finally, water can also be defined as:

```

MATERIAL 9 G4_WATER 0 -1

```

It is the responsibility of the user to make geometries that do not contain errors. In particular, to make geometries in which volumes do not overlap.

## 2.2 Source

The source is defined with the **SOURCE** keyword. The source is alpha particles that can be emitted either isotropically and uniformly distributed inside a volume, or distributed on a disk with a certain direction (*beam mode*). There is one alpha particle per history in the run. The energies of the alpha particles are sampled according to a probability distribution, given in the input. This distribution is, in principle, discrete, but each line can be widened according to a Gaussian distribution.

The following entries have to be provided in the input file:

```

SOURCE SPosType  $\lambda_1$   $\lambda_2$  ...  $\lambda_{N\lambda}$ 
SNorm      NS
SourceName1    AlphaEnergy1    AlphaIntensity1    [AlphaSigma1]
SourceName2    AlphaEnergy2    AlphaIntensity2    [AlphaSigma2]
...
SourceNameNS    AlphaEnergyNS    AlphaIntensityNS    [AlphaSigmaNS]
ENDSOURCE

```

Where each of the entries is:

**SPosType** [integer] – The **SPosType** flag, together with the  $\lambda_i$  values that follows it, defines the initial position and momentum direction of the source. There are various possibilities:

**SPosType** = 0: then the source will be emitted isotropically from one of the volumes defined in the **VOLUME** field. In this case **N $\lambda$** =1 and  $\lambda_1$  has to be set to the desired **VoIID**. For example, **SPosType** = 0 and  $\lambda_1$ =14 means that the source will be emitted uniformly distributed from volume with **VoIID** =14.

**SPosType** > 0: More general sources can be defined. There are three types of volumes can be defined for the moment, the same as in the **VOLUME** field: a sphere (**SPosType** = 1, with **Nλ**=4), a parallelepiped (**SPosType** = 2, with **Nλ**=6) or a cylinder (**SPosType** = 3, with **Nλ**=5). In all these cases the source is emitted isotropically.

**SPosType** = -1 : (*beam mode*) the source is emitted from a plane disk, with a certain momentum direction.

**λ<sub>1</sub> λ<sub>2</sub> ... λ<sub>Nλ</sub>** [real] – parameters used to define the dimensions and position of the source volume.

If **SPosType** = 0, then **Nλ**=1 and **λ<sub>1</sub>** has to be set to the desired **VoID**.

If **SPosType** > 0, they have **almost** the same meaning as in the **VOLUME** field. The only difference is that the **translation vector** (vx,vy,vz) is **respect to the world volume** for the source. For example, for **SPosType** = 1, **λ<sub>1</sub>** is the sphere radius and (**λ<sub>2</sub>**, **λ<sub>3</sub>**, **λ<sub>4</sub>**) the origin of the sphere, with all **λ<sub>i</sub>** in cm. If **SPosType** < 0, then the first **λ<sub>i</sub>** values have the same meaning as for - **SPosType**, and the last three entries corresponds to the momentum direction in the x, y and z axis. No normalization is required.

If **SPosType** = -1 (*beam mode*), then **Nλ**=8 and the alpha particles are emitted inside a plane disk perpendicular to the Z axis and centered in (**λ<sub>1</sub>**, **λ<sub>2</sub>**, **λ<sub>3</sub>**), in cm, with a momentum direction given by (**λ<sub>4</sub>**, **λ<sub>5</sub>**, **λ<sub>6</sub>**). No normalization is needed from the momentum direction. The radius of the disk is given by **λ<sub>7</sub>**, in cm. The source is emitted uniformly in the disk if **λ<sub>8</sub>** is negative or zero, and with a Gaussian distribution with standard deviation equal to **λ<sub>8</sub>** (in cm) in X and Y otherwise.

**SNorm** [real] – If positive, this is the normalization factor for the histograms in the output. If not positive, then the normalization factor is the sum of all the **AlphaIntensity<sub>i</sub>** values. The histograms in the output are normalized to be per source α particle multiplied by the normalization factor.

**NS** [integer] – Number of lines below which will define the source energy spectrum. Each line will contain three or four entries, which are used to model the energy spectrum of the alpha particle source.

**SourceName<sub>i</sub>** [string] – This entry is used, together with **AlphaEnergy<sub>i</sub>**, to define the type of contribution to the energy spectrum of the source. There are three possibilities, which are listed below.

**AlphaEnergy<sub>i</sub>** [real] – If positive, energy (in MeV) of the *i*<sup>th</sup>-alpha particle. A negative value indicates that the *i*<sup>th</sup> contribution is defined with **SourceName<sub>i</sub>** (see below).

**AlphaIntensity<sub>i</sub>** [real] – Intensity of the *i*<sup>th</sup> contribution to the source. The amount of source alpha particles generated by the program is proportional to this number. If **SNorm** is negative or zero, then this value is also used for normalizing the output histograms.

**AlphaSigma<sub>i</sub>** [real] – This is an optional entry. Can be omitted, and thus it takes the default value (default value: -1 MeV). If positive, the energy of the *i*<sup>th</sup>-alpha particle is sampled according to a Gaussian distribution with a standard deviation **AlphaSigma<sub>i</sub>**, in MeV.

There are three possible contributions to the source energy spectrum:

**Case A:** If **SourceName<sub>i</sub>** is set to “Chain\_Th232”, “Chain\_U235” or “Chain\_U238” then the entire alpha particle energies and intensities of the <sup>232</sup>Th, <sup>235</sup>U or <sup>238</sup>U decay series in secular equilibrium, respectively, will be added to the initial alpha energy spectrum. In this case, the entry **AlphaEnergy<sub>i</sub>** will not be used by the code and **AlphaIntensity<sub>i</sub>** will be the total intensity of the given decay series.

**Case B:** If **SourceName<sub>i</sub>** is not set to any of the values listed in Case A and **AlphaEnergy<sub>i</sub>** < 0, then **SourceName<sub>i</sub>** is assumed to be the name of one of the files in the SaG4n database, inside the “AlphaSpectra” directory. The alpha energy spectrum in the corresponding data file, which in most cases corresponds to radioactive decays, will be then added to the initial alpha energy spectrum. The total intensity of that spectrum will be in this case **AlphaIntensity<sub>i</sub>** divided by the absolute value of **AlphaEnergy<sub>i</sub>** (the idea here is to set the abundance in **AlphaIntensity<sub>i</sub>** and the half-life in **AlphaEnergy<sub>i</sub>**). As an example, if **SourceName<sub>i</sub>** is set to “Pu239” and **AlphaEnergy<sub>i</sub>**=-1, then the entire alpha energy spectrum of the <sup>239</sup>Pu decay will be added to the source with an intensity **AlphaIntensity<sub>i</sub>**. If this option is used, be sure that the **SAG4NDATABASEDIR** keyword is also in the input file.

**Case C:** If **SourceName<sub>i</sub>** is not set to any of the values listed in Case A and **AlphaEnergy<sub>i</sub>** ≥ 0, then a discrete alpha particle with energy **AlphaEnergy<sub>i</sub>** will be added to the initial alpha energy spectrum with intensity **AlphaIntensity<sub>i</sub>**. In this case the value of **SourceName<sub>i</sub>** is not used.

#### Example 1:

```
SOURCE 3 10 20 +15 0 0
1.00 3
ThreeMeVAlpha 3.00 1.00
FiveMeVAlpha 5.00 1.00
EightMeVAlpha 8.00 1.00
ENDSOURCE
```

These lines define a source where the α particles are emitted isotropically and uniformly distributed inside a cylindrical volume of 10 cm radius and 20 cm length, with the center in x=15 cm, y=z=0 cm, with its symmetry axis parallel to the Z axis. The α particles are emitted with 3, 5 or 8 MeV, with the same probability.

#### Example 2:

```
VOLUME 15 Cylinder01 9 3 0 - 10 20 +15 0 0
SOURCE 0 15
1.00 3
ThreeMeVAlpha 3.00 1.00
FiveMeVAlpha 5.00 1.00
EightMeVAlpha 8.00 1.00
ENDSOURCE
```

These lines define a source which is the same as the one in the previous example.

**Example 3:**

```
VOLUME 15 Cylinder01 9 3 0 - 10 20 +15 0 0
SOURCE 0 15
1.00 3
Chain_Th232 0 30.00
Chain_U235 0 50.00
Chain_U238 0 20.00
ENDSOURCE
```

The spatial distribution of the source is the same as before, but now the energies of the alpha particles are sampled from the  $^{232}\text{Th}$  decay series 30% of the times, from the  $^{235}\text{U}$  decay series 50% of the times and from the  $^{238}\text{U}$  decay series 20% of the times. In all the cases the decay series are in secular equilibrium.

**Example 4:**

```
VOLUME 15 Cylinder01 9 3 0 - 10 20 +15 0 0
SOURCE 0 15
1.00 2
Pu239 -1 90.00
Pu240 -1 7.00
Pu242 -1 3.00
ENDSOURCE
```

The spatial distribution of the source is the same as before, but now the energies of the alpha particles are sampled according to the decay spectrum of  $^{239}\text{Pu}$  90% of the times,  $^{240}\text{Pu}$  7% of the times and  $^{242}\text{Pu}$  3% of the times.

**Example 5:**

```
SOURCE -1 3 2 1 0 0 1 2 -1
1.00 2
ThreeMeVAlpha 3.00 1.00 0.2
FiveMeVAlpha 5.00 1.00 0.2
ENDSOURCE
```

These lines define a source in beam mode. They are emitted in a disk centered in (3,2,1) cm and perpendicular to the Z axis, with momentum direction (0,0,1). The disk has a radius of 2 cm and the alpha particles are emitted uniformly distributed inside the disk. The energies of the alpha particles are sampled according to a distribution made of two gaussians, both with the same probability, centered at 3 and 5 MeV and with 0.2 MeV standard deviations.

## 2.3 Output

The information in the output is controlled by two keywords: **OUTPUTTYPE** and **OUTPUTFILE**. The **OUTPUTTYPE** keyword controls the type of information to be retrieved by the program; and the **OUTPUTFILE** keyword is used to provide the name of the output file(s).

The program can generate two types of outputs. The first is a set of histograms. These histograms are of three types: energy distributions of the neutrons generated in each volume; alpha particle flux in each volume; and energy spectrum of the source alpha particles. Histograms are written to a file either in ROOT format [2] (rootfile) or in text (ASCII) format. There, a neutron energy spectrum histogram and an alpha particle flux histogram will appear for each volume defined in the geometry, with the exception of the world volume. The names of these histograms will be NSpec\_XXX and AFlux\_XXX, where XXX is the **VolName** of the corresponding volume. The energy spectrum of the source will appear with the name "Source\_00".

The second type of output is a text file containing a list of the neutrons and gamma rays generated in the calculation. For each neutron and gamma ray, a new line will appear in the output file with its energy, momentum, position ...

The neutron yield in each volume, defined as the number of neutrons produced by source alpha particle and multiplied by the normalization provided in the definition of the source (section 2.2), can be computed as the integral of the neutron energy spectrum histogram. The uncertainty in this integral, obtained from the uncertainties in the bins under the assumption that there are no correlations, is usually a very good approximation of the uncertainty in the yield due to counting statistics. A more precise value, however, is stored in the 0-bin (*underflow* bin) of the histogram. This is, the 0-bin of the NSpec\_XXX histograms contain the total neutron yield together with the uncertainty due to counting statistics.

The **OUTPUTFILE** keyword has to be followed by the following entry:

### **OUTPUTFILE** **FName**

Where:

**FName** [string] – Is the base name for the output file. The base name should be provided without extension. The program will create eventually two output files: one root or text file with the histograms, whose name will be the one provided here plus the extension ".root" or ".txt"; and other text file with the list of generated neutrons and gamma rays, whose name will be the one provided here plus the extension ".out".

The **OUTPUTTYPE** keyword has to be followed by the following entries:

**OUTPUTTYPE**    **OutType1** **OutType2** **OutputFormat**

Where each of the entries is:

**OutType1** [integer] – This entry controls whether or not to write the file with the neutron energy spectra and the alpha particle fluxes. Two possibilities are allowed:

**OutType1** = 0 – The file with the histograms is not generated.

**OutType1** = 1 – The file with the histograms is generated.

**OutType2** [integer] – This entry controls how the text file with the list of generated neutrons and gamma rays is generated. Three possibilities are allowed:

**OutType2** = 0 – No file is generated.

**OutType2** = 1 – The text file with the list of generated neutrons and gamma rays is generated. Each line in the output file corresponds to a secondary particle. There are 10 columns, with the following information and in this order: event number (history in the run), particle name (neutron or gamma), energy (MeV), weight, position (three entries, corresponding to x, y and z coordinates, in cm), and momentum direction (three entries, corresponding to the projections of the momentum direction, which is a unitary vector, in the x, y and z axis, respectively) of the secondary particle.

**OutType2** = 2 – Same as **OutType2** = 1, but 10 more columns are added, in the following order: Z of the nucleus involved in the reaction, A of the nucleus involved in the reaction, energy of the  $\alpha$  particle (in MeV) at the time of the interaction, energy of the  $\alpha$  particle (in MeV) at the beginning of the history run, position (three entries, corresponding to x, y and z coordinates, in cm), and momentum direction (three entries, corresponding to the projections of the momentum direction, which is a unitary vector, in the x, y and z axis, respectively) of the  $\alpha$  particle at the beginning of the history run.

**OutputFormat** [integer] – This entry controls the format in which the output files are written. Two options are allowed:

**OutputFormat** = 1 – The file with the histograms is written in text (ASCII) format (\*).

**OutputFormat** = 2 – The file with the histograms is written in root format.

By default **OutType1** = 1, **OutType2** = 0 and **OutputFormat** = 2.

(\*) The format for the histograms written in ASCII is the following. For each histogram, the following lines appear in the file. First, a line with three entries, in this order: the name of the histogram, the number of bins (NBins) and the upper limit of the histogram (in MeV). The lower limit of the histogram is always 0 MeV. This line is followed by NBins+2 lines, each with three entries, in this order: lower limit of the bin (in MeV), bin content, and uncertainty of the bin due to counting statistics.



## 2.4 Rest of the input

The rest of the input file is given by the following keywords.

### **BIASFACTOR** **BFactor**

Where:

**BFactor** [real] – The nuclear cross section in all the volumes defined in the geometry is biased by this factor. If negative or zero, no biasing is applied. This keyword is optional, and the default value of **BFactor** is -1 (no biasing). Given the usual yields of  $10^{-9} - 10^{-5}$  neutrons /  $\alpha$ , bias factors in the order of  $10^4$  are needed to make the estimation of the yields viable with this approach.

NOTE: The optimal point depends on the case and the user should explore convergence of the results before relying on the results

### **MAXSTEPSIZE** **StepMax**

Where:

**StepMax** [real] – Is the maximum allowed step size (in cm) for the transport of the alpha particles. The smaller this value is, the more detailed the transport of alpha particles is made, but the slower the execution of the program. This keyword is optional, and the default value of **StepMax** is 0.001.

### **NEVENTS** **NEvents**

Where:

**NEvents** [integer] – Is the number of histories to be run (or number of *events*). This keyword is optional, and the default value of **NEvents** is 100000.

### **SEED** **Seed**

Where:

**Seed** [integer] – Is the seed for the random number generator. This keyword is optional, and the default value of **Seed** is 1234567.

### **INTERACTIVE**

No entries are provided after the **INTERACTIVE** keyword. If this keyword is in the input file, then Geant4 runs in interactive mode.

### **DONOTKILLSECONDARIES**

No entries are provided after the **DONOTKILLSECONDARIES** keyword. By default in this program all the secondary particles are not transported but killed when created. If this keyword is in the input file, then secondary particles are transported.

### **SAG4NDATABASDIR Path**

Where:

**Path [string]** – Is the data path to the SaG4n database, which is released together with the code and is located in “[...]/SaG4n.XX.YY/data”.

## **3 Examples**

There are six sets of examples in six folders:

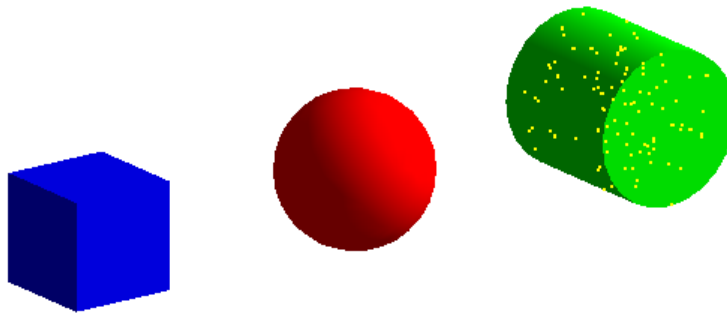
- geometry: Special attention is paid to show what can be done in terms of generating the volumes.
- yields: examples for the yield of a  $^{232}\text{Th}$  source in different elements are provided.
- components: examples of usage for calculating the yields of the different chains and subchains on simple detector components.
- basic01: additional basic examples, focused in the definition of the materials and the sources.
- beam: a simple example with an alpha particle beam.
- fuel: neutron emission in  $\text{PuO}_2$ , using the SaG4n internal database to get the  $\alpha$ -particle energy spectra.

Here we will only describe in detail the pieces of the code that are relevant for each specific example. The definitions of the volumes are explained in most cases because is probably the part that needs more care.

### **3.1 geometry**

#### **3.1.1 geom01**

A box, a sphere and a cylinder centered along the x axis. The source is defined independently but placed coincident with the cylinder.



*Figure 1: Geometry of the geom01 example visualized with vis01.mac*

The first relevant line is:

```
# A sphere made of CH2 placed in the center:
VOLUME 77 Sphere01      7 1 0 - 5 0 0 0
```

A volume is defined with VolID 77 and name Sphere01. It is made of material 7 (CH<sub>2</sub>, defined later), it is of type 1 (sphere) and its mother volume is 0 (the world). The dash is a dummy word to separate the definition from the dimensions. It is irrelevant and can be whatever word. The sphere has radius of 5 cm and is placed in the (0,0,0) coordinate of the world (the position is with respect to the mother volume).

```
# A parallelepiped made of C placed at -20 cm in the X axis:
VOLUME 49 Box01         8 2 0 - 7 7 7 -20 0 0
```

A volume is defined with VolID 49 and name Box01. It is made of material 8 (C, defined later), it is of type 2 (parallelepiped) and its mother volume is 0 (the world). Its dimensions are  $L_x = 7$  cm,  $L_y = 7$  cm,  $L_z = 7$  cm, and it is placed in the coordinate (-20,0,0).

```
# A cylinder made of H2O placed at +20 cm in the X axis:
VOLUME 54 Cylinder01    9 3 0 - 5 10 +20 0 0
```

A volume is defined with VolID 54 and name Cylinder01. It is made of material 9 (H<sub>2</sub>O, defined later), it is of type 3 (cylinder) and its mother volume is 0 (the world). Its dimensions are  $R = 5$  cm,  $L_z = 10$  cm, and it is placed in the coordinate (20,0,0). In this first version of the code, cylinders are always defined along the z axis.

```
# MATERIALS:
MATERIAL 7 CH2 0.93 4
1001 1.99977
1002 0.00023
6012 0.9893
6013 0.0107
ENDMATERIAL
```

Material number 7 is named CH<sub>2</sub>, given a density of 0,93 g/cm<sup>3</sup> and it is stated that will be made of 4 isotopes. First isotope is <sup>1</sup>H, which contributes to the compound with an atomic fraction of 1,99977. Then <sup>2</sup>H, <sup>12</sup>C and <sup>13</sup>C atomic contributions are written. Isotopes are defined with the code Z\*1000 + A. One can see that in this case the sum of the atomic fractions is 3, which corresponds to the CH<sub>2</sub> molecule that wants to be defined. This is not necessary and, as it is evident by this and the following definitions, it does not need to be normalized either. The number of atoms per unit volume is completely defined by the density and the ratio between the atomic fractions.

```
MATERIAL 8 C 2.266 2
6012 0.9893
6013 0.0107
ENDMATERIAL
```

```
MATERIAL 9 H2O 1.00 5
1001 1.99977
1002 0.00023
8016 0.99757
8017 0.00038
8018 0.00205
ENDMATERIAL
```

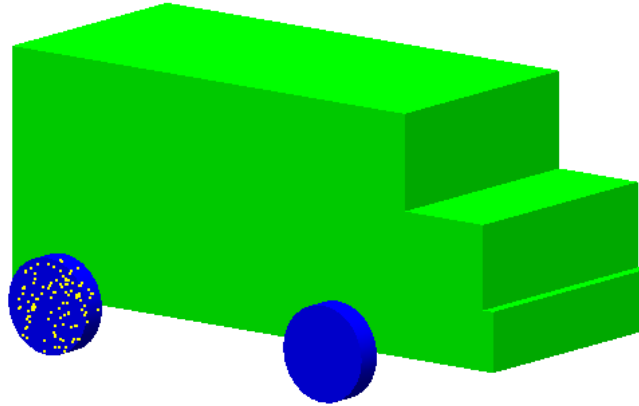
The rest of the materials are defined following the same principle and do not need specific explanation.

```
SOURCE 3 5 10 +20 0 0
1.00 1
Dummy 8.00 1.00
ENDSOURCE
```

The source is a cylinder (3) of R = 5 cm and L<sub>z</sub> = 10 cm placed at (20,0,0), so alphas are emitted from Volume 54, Cylinder01.

### 3.1.2 geom02

A four-wheeled van, with a central body made of several boxes is defined.



*Figure 2: Geometry of geom02 example.*

```
VOLUME 1 BigBox      7 2 0 - 20 10 10 0 0 0
VOLUME 2 MedBox01    7 2 0 - 4 6 10 12 -2 0
VOLUME 3 MedBox02    7 2 0 - 0.5 2.5 10 14.25 -3.75 0
VOLUME 4 Wheels01    8 3 0 - 2 1 -7 -5 6
VOLUME 5 Wheels02    8 3 0 - 2 1 +7 -5 6
VOLUME 6 Wheels03    8 3 0 - 2 1 -7 -5 -6
VOLUME 7 Wheels04    8 3 0 - 2 1 +7 -5 -6
```

The main body of the van is defined in the first line, with VolID 1 and named BigBox. It is made of material 7 and it's a volume of type 2 (parallelepiped) defined with the world as mother volume (0). Its dimensions are  $L_x = 20$  cm,  $L_y = 10$  cm,  $L_z = 10$  cm, and it is placed in the coordinate (0,0,0).

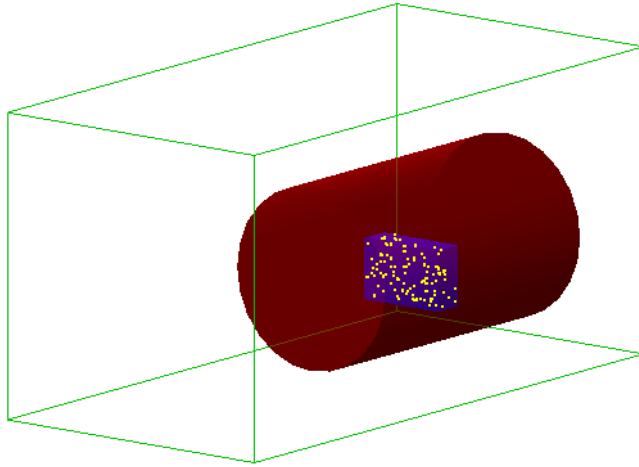
The car nose is numbered with VolID 2 and defined in the second volume as MedBox01, made of material 7, being a parallelepiped (2) hanging from the mother volume (0). Its dimensions are  $L_x = 4$  cm,  $L_y = 6$  cm,  $L_z = 10$  cm, and it is placed at (12,-2,0). Coordinate Z is across the paper in Illustration 1. This volume is shifted 12 cm along the X axis (10 cm from the half length of the BigBox + 2 cm from its own length) to avoid overlaps. The shifting along the Y axis is to make its bottom plane coincident with the bottom plane of BigBox.

The car bumper is defined as MedBox02 following the same concept as the nose, so won't be explained here.

The wheels are defined as made of material 8, being cylinders in the mother volume with  $R = 2$  cm and  $L_z = 1$  cm. They are placed at  $(\pm 7, -5, \pm 6)$ . The "+" sign in X corresponds to the front wheels and the "-" sign to the back wheels. The "+" sign in Z corresponds to the right hand side and the "-" sign to the left hand one. All wheels are in the negative side of y (because they are in the bottom of the van).

### 3.1.3 geom03

The volume consists of a box, embedded in a cylinder, embedded in a box.



*Figure 3: Set of embedded geometries as defined in example geom03. The overlaps are dealt with by Geant4 by defining the volumes hierarchically as mother volumes.*

```
VOLUME 12 Box01    7 2 0 - 10 10 20 0 0 0
```

The outer box, Box01, has VolID12, is made of material 7 (CH2) is a parallelepiped (2) and is embedded in the volume 0. Its size is  $L_x = 20$  cm,  $L_y = 10$  cm,  $L_z = 10$  cm and is placed in the center of the world (0,0,0).

```
VOLUME 14 Cylinder01  8 3 12 - 3 10 1 -1 -3
```

The cylinder, with VolID 14 and named Cylinder01, is made of material 8 (carbon) and is indeed a cylinder (3) which is embedded in VolID 12 (which is defined as the mother volume). This is a simple way within Geant4 to define volumes that are completely inside other volumes and not worrying about overlaps. If two volumes are occupying the same volume in Geant4 and don't have a hierarchy, errors are expected.

```
VOLUME 25 Box02    9 2 14 - 3 2 1 0.5 -0.5 0.5
```

The inner box is given VolID 25, named Box02, made of material 9 (H2O). It is indeed a parallelepiped (2) with VolID 14 as its mother volume.

The innermost volume, VolID 25, is defined as the alpha source after the definition of the materials:

```
SOURCE 0 25
1.00 1
Dummy 8.00 1.00
ENDSOURCE
```

The first "0" states that a volume already defined will be used as source, and 25 states which volume will be (VolID) . The normalization factor is 1.00 and alphas of one energy

will be emitted. This energy is set in the following line, with a dummy introduction word, and the energy (8.00) and its relative intensity. In this case the relative intensity does not make much sense because there aren't more alphas to weight against, but a number needs to be written in any case.

### 3.1.4 visualizing macros

If the inputs in the geom folder are run in interactive mode, the respective macros in the vis/ folder can be used to visualize the geometry. For the last case, after typing

```
$ ./build/SaG4n inputs/examples/geometry/geom01.inp
```

One can visualize it typing

```
$ /control/execute inputs/examples/geometry/vis01.mac
```

The macros might need to be adapted to the Geant4 visualization options of the user.

## 3.2 yields

The yields for different materials exposed to  $^{232}\text{Th}$  decay chain in secular equilibrium. These are some of the results reported in [3]. Only the lines in the MATERIALS and OUTPUTFILE fields change from one example to the other and will be commented here.

```
SOURCE 1 0 0 0 0
1.00 26
90232 4.0123 78.2
90232 3.9472 21.7
90232 3.8111 0.069
90228 5.42315 73.4
...
ENDSOURCE
```

This is a point source defined as sphere (volume of type 1) of radius 0 and placed in the (0,0,0) coordinate. The number to normalize to is 1.00 and 26 different alphas will be emitted by the source, corresponding to the alphas that can be produced in a  $^{232}\text{Th}$  decay. In this case the dummy word defines the parent nucleus of the alpha in (Z\*1000 + A) format, then the energy (4.0123 MeV in the first case) and its relative intensity. Only the first 4 alphas are listed here, because they are enough to clarify the example. The SOURCE field needs to be ended with the ENDSOURCE word.

There are 15 different materials, each of them defined in the input files yield01.inp, yield02.inp,..., yield15.inp. The same inputs but with a different way of defining the materials and the source, are provided in yield01\_v2.inp, yield02\_v2.inp,..., yield15\_v2.inp. There the materials are defined using elements instead of isotopes, and the  $^{232}\text{Th}$  decay chain implemented inside SaG4n is used.

### 3.3 components

We present the result of evaluating the neutron yield for two relatively simple geometries that are paradigmatic cases of the importance of the interfaces and, hence, full simulations:

- 1) a copper cable with a fluorine-based insulator,
- 2) a PCB substrate with copper and liquid argon on each side, and

For each of the examples, the  $^{232}\text{Th}$  chain and the different parts of the  $^{238}\text{U}$  chain are considered. Here we will only explain one example of each geometry.

One can comment away the different volumes and change the materials to study the effect in the total yield. The simulation shows the sizable effect of interfaces between materials with high  $(\alpha, n)$  cross section and materials with small mass which contribution to the neutron budget is often considered negligible.

#### 3.3.1 cable\_U238\_mid

A cylinder embedded in another cylinder are defined in the VOLUME section.

```
VOLUME 11 CuCable      21 3 12 DummyWord 0.025 2 0 0 0
VOLUME 12 fepInsul     22 3 0  DummyWord 0.1   2 0 0 0
```

The inner one is defined as VolID 11 and called CuCable. It's made of material 21, is indeed a cylinder (3) and is embedded in the volume with VolID 12. Its radius is 0.025 cm and it's length 2 cm. The outer one is defined as VolID 12 and called fepInsul. It's made of material 22, is indeed a cylinder (3) and is embedded in the "world" volume (0). Its radius is 0.1 and its length 2 cm, too. Both of them are placed in the origin of coordinates.

Then in the MATERIAL section,

```
MATERIAL 21 Cu 8.96 2
29063 0.6915
29065 0.3085
ENDMATERIAL
```

the material of the inner cylinder (21) is defined as "Cu", with a density of 8,96 g/cm<sup>3</sup> and having two isotopes,  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$  -specified in Z\*1000 + A format- with 0,6915 and 0,3085 atomic fraction, respectively. Each material needs to be finished with the ENDMATERIAL word.

```
MATERIAL 22 FEP 2.15 3
6012 0.9893
6013 0.0107
9019 3.0
ENDMATERIAL
```

Then material 22, the one corresponding to the outer cylinder is defined as "FEP". It has density of 2.15 g/cm<sup>3</sup> and is made of 3 isotopes:  $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{19}\text{F}$ . The atomic fractions state that there is the natural abundance of  $^{12}\text{C}$  and  $^{13}\text{C}$  and that there are 3 fluorine atoms per C atom.



```

MATERIAL 23 LAr 1.4 1
18040 1.
ENDMATERIAL

```

A third material is defined in case the user wants to study the effect of having this geometry in a LAr bath. The definition of the volume is left as an exercise. In any case, adding this material should only have an effect in the case of very thin insulators.

The source of alphas

```

SOURCE 0 11
1.0 24

```

is defined as one of the existing volumes (by starting with a 0) and in particular VolID 11, the inner cylinder. The yield will be normalized to 1.0 and alphas with 24 different energies will be shot. Then a dummy word, in this case specifying the parent nuclei, is followed by the energy and the relative intensity of this alpha. It is clear that relative intensities do not need to be normalized.

```

88226 4.78434 93.84
88226 4.601 6.16
88226 4.34 0.0065
88226 4.191 0.001
88226 4.16 0.00027
86222 5.48948 99.92
86222 4.986 0.078
86222 4.826 0.0005
84218 6.00235 99.97890022
84218 5.181 0.00109978
85218 6.756 0.00071928
85218 6.693 0.017982
85218 6.653 0.00127872
86218 7.1292 1.9974e-05
86218 6.5311 2.54e-08
83214 5.516 0.009408
83214 5.452 0.012936
83214 5.273 0.001392
83214 5.184 0.0001464
83214 5.023 5.04e-05
83214 4.941 6e-05
84214 7.68682 99.96550252
84214 6.9022 0.010397504
84214 6.6098 5.99856e-05
ENDSOURCE

```

The source definition needs to end with the ENDSOURCE word. As the name of the input states, in this case we are simulating what we call the  $^{238}\text{U}$  middle chain, with all the alpha emitters between  $^{226}\text{Ra}$  and up to the  $^{210}\text{Pb}$  “waiting point”, with the latter excluded.

### 3.3.2 pcb\_Th232

In this example we define two planar bodies with an interface in  $Z=0$  and submerged in Liquid Argon.

```
VOLUME 11 CuPCB          21 2 13 Dummy  5  5 0.05 0 0  0.025
VOLUME 12 SubstratePCB    22 2 13 Dummy  5  5 0.01 0 0 -0.005
VOLUME 13 LAr             23 2 0  Dummy 10 10  10 0 0  0
```

First, a volume with VolID 11, called “CuPCB” is defined. It is made of material 21, is a parallelepiped embedded inside the volume with VolID 13. Its dimensions are  $5 \times 5 \times 0,05 \text{ cm}^3$  and is shifted by the vector  $(0, 0, 0.025)$ . This shifting in  $Z$  is introduced to place the interface between materials at  $Z=0$ .

The second volume, with VolID 12 and called “SubstratePCB” is made of material 22, is a parallelepiped and is also embedded in VolID13. Its dimensions are  $5 \times 5 \times 0,01 \text{ cm}^3$  and is shifted towards negative  $Z$  by the vector  $(0, 0, -0.005)$  for the already explained reason. Note that there are no overlaps in the geometry at this point.

The third volume, with VolID 13 and called “LAr”, is made of material 23, is a parallelepiped and hangs directly from the WORLD volume (its mother volume is 0). Its dimensions are  $10 \times 10 \times 10 \text{ cm}^3$  and sits in the origin of coordinates. The other two geometries that were formerly defined have overlaps with this volume, but since the latter is actually defined as their mother volumes this induces no conflict.

Note that the volume section does **not** need any specific ending word.

Only MatID 22 will be described in this section (see the explanation of the other examples for the other ones).

```
MATERIAL 22 kevlar 1.44 9
1001 9.998
1002 0.002
6012 13.8502
6013 0.1498
7014 1.992
7015 0.008
8016 1.9952
8017 0.0008
8018 0.004
ENDMATERIAL
```

Material with ID 22 is named “kevlar”, has a density of  $1,44 \text{ g/cm}^3$  and is made of 9 isotopes,  $^1\text{H}$ ,  $^2\text{H}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{14}\text{N}$ ,  $^{15}\text{N}$ ,  $^{16}\text{O}$ ,  $^{17}\text{O}$  and  $^{18}\text{O}$ . The atomic fractions are calculated to account for the isotopic abundances and for the average formula of kevlar ( $\text{C}_{14}\text{H}_{10}\text{N}_2\text{O}_2$ ).

The source is placed in one of the already defined volumes (by starting with a 0), and in particular VolID 11 is chosen, the CuPCB. The yield will be normalized to 1.0, meaning that the results will be in neutrons per alpha in the chain, and 26 alphas are considered. Each of them is defined starting with a dummy word, which in this case states the parent

nucleus, and followed by its energy and relative intensity. Relative intensities do not need to be normalized.

```
SOURCE 0 11
1.0 26
90232 4.0123 78.2
90232 3.9472 21.7
90232 3.8111 0.069
90228 5.42315 73.4
90228 5.34036 26.0
90228 5.211 0.408
90228 5.173 0.218
90228 5.138 0.036
88224 5.68537 94.92
88224 5.4486 5.06
88224 5.161 0.0071
88224 5.051 0.0076
88224 5.034 0.003
86220 6.28808 99.886
86220 5.747 0.114
84216 6.7783 99.9981
84216 5.985 0.0019
83212 6.08988 9.746928
83212 6.05078 25.125654
83212 5.768 0.61098
83212 5.626 0.0564258
83212 5.607 0.406122
83212 5.481 0.0046722
83212 5.345 0.0003594
83212 5.302 3.9534e-05
84212 8.78486 64.06
ENDSOURCE
```

In this case the source is the  $^{232}\text{Th}$  chain. The source definition must end with the ENDSOURCE word.

### 3.4 basic01

There are two types of input examples in this folder.

In concrete01.inp the alpha particles of the  $^{232}\text{Th}$  decay series in secular equilibrium are emitted inside a concrete block. The output is a root file with the generated neutron energy spectrum and the list-mode file with the generated neutrons and  $\gamma$ -rays. The input file concrete02.inp is exactly the same as concrete01.inp, but the concrete material has been

defined using mass fraction abundances instead of atomic fractions. These two examples can be used to check that the same result is obtained in both cases.

In source01.inp alpha particles are generated inside a block of  $\text{CF}_2$ , and the output is a root file with the generated neutron energy spectrum. The energy distribution of the source alpha particles is a mix of the  $^{232}\text{Th}$  (30%),  $^{235}\text{U}$  (50%) and  $^{238}\text{U}$  (20%) decay series in secular equilibrium. The normalization factor of the source is 1. On the other hand, source02.inp, source03.inp and source04.inp are the same as source01.inp, but the source contains only the  $^{232}\text{Th}$  (source02.inp),  $^{235}\text{U}$  (source03.inp) or  $^{238}\text{U}$  (source04.inp) spectra. The normalization factors are in these cases 0.30, 0.50 and 0.20, respectively. These four inputs can be used to check that the results obtained from source01.inp are the same as the sum of the results from source02.inp, source03.inp and source04.inp.

### 3.5 beam

There is just an input: beam01.inp. There alpha particles with energies sampled according to a Gaussian distribution with mean 10 MeV and standard deviation 0.5 MeV are emitted in the (0,0,1) direction from a flat disk perpendicular to the Z axis, centered in (0,0,-1) cm, with 2 cm radius. The position of the alphas are sampled according to a 2D-gaussian distribution centered in the center of the disk and with 0.7 cm standard deviations in X and Y, and always inside the disk (i.e. 2 cm is the maximum distance from the Z axis).

The alpha particle beam impinges into a 3 cm in radius and 1 cm length aluminum sample.

### 3.6 fuel

There are two inputs in this folder. Both of them should provide (practically) the same result. The purpose of these inputs is to calculate the neutron emission in  $\text{PuO}_2$  due to ( $\alpha$ ,n) reactions from the Pu  $\alpha$ -decay. The isotopic composition of Pu is:  $^{238}\text{Pu}$  (0.1%),  $^{239}\text{Pu}$  (59.9%),  $^{240}\text{Pu}$  (20%),  $^{241}\text{Pu}$  (10%) and  $^{242}\text{Pu}$  (10%).

Important note: there is a bug in Geant4 in some versions older than geant4-v11.2.1 which makes a segmentation fault when transporting alpha particles in materials containing elements heavier than uranium ([https://bugzilla-geant4.kek.jp/show\\_bug.cgi?id=2586](https://bugzilla-geant4.kek.jp/show_bug.cgi?id=2586)). Thus, this inputs should be run with an appropriate Geant4 version or, alternatively, the Pu isotopes in the material definition may be changed with uranium isotopes, and similar results should be obtained.

The calculation is similar to those in section 3.2, but here we make use of the SaG4n database to produce the source. Each Pu isotope will contribute to the total  $\alpha$ -source with their own  $\alpha$  energy spectra, with a weight proportional to its isotopic abundance multiplied by its activity; or, equivalently, to its isotopic abundance divided by its half-life.

In fuel01.inp the source is written as:

```
SOURCE 1 0 0 0 0
1.00 5
Pu238 -1 0.00114025
```

```

Pu239 -1 0.00248445
Pu240 -1 0.00304832
Pu241 -1 0.00172861
Pu242 -1 2.681e-5
ENDSOURCE

```

Here the different  $\alpha$  spectra are obtained from the files in `./data/AlphaSpectra/`, with a contribution proportional to the number in the third column (0.00114025, 0.00248445 etc.). These numbers have been computed by dividing the isotopic abundances by the corresponding half-lives.

In `fuel02.inp` the source is written as:

```

SOURCE 1 0 0 0 0
1.00 5
Pu238 -87.7      0.1
Pu239 -24110    59.90
Pu240 -6561     20.00
Pu241 -5785     10.00
Pu242 -373000   10.00
ENDSOURCE

```

Where now the second column contains the half-lives, in years, and the third column the abundances. Again, the contributions are proportional to the values in the third column divided by the values in the second column (see section 2.2), thus providing the same result as `fuel01.inp`.

## 4 References

- [1] S. Agostinelli et al., Nucl. Instrum. Methods A 506, 250 (2003).
- [2] Rene Brun and Fons Rademakers, Nucl. Inst. and Meth. A 389, 81 (1996). See also <http://root.cern.ch/>
- [3] E. Mendoza et al., Nucl. Instrum. Methods A 960, 163659 (2020).