Particle Transport Computer Modeling for HPGe Screeners

Pauline M. Dredger (Kara Keeter, Keenan Thomas, Brianna Mount) School of Natural Sciences, Black Hills State University, Spearfish, SD 57799

Why Underground?

The hunt for physics such as neutrino-less double beta decay and the nature of dark matter involve looking for particle interactions that are exceptionally rare with the most sensitive detectors physicists can build. Cosmic rays, both of which bombard the surface of earth at all times, present a large and unwanted source of noise in these extremely sensitive detectors. By assembling the experiments underground with nearly a mile of rock between the detectors and the earth's surface, physicists can achieve a much quieter environment and have a much better chance of detecting the interactions for which they are searching.

Radio-pure Materials

Cosmic rays are not the only source of background for supersensitive detectors in rare-particle interactions. The everyday naturally occurring radioactivity of alpha, beta, and gamma decay also causes problems for researchers and their instruments, even after the experiments have been moved underground. Because almost everything is slightly radioactive (including humans) the issue can come from the very materials out of which the detector is constructed. No matter how good the detector shielding is, if radioactive isotopes exist inside the protective barriers, finding the desired signal, should it appear, will be difficult for the researchers. Each component of the experiments must be tested in a separate detector to determine how much it will contribute to the background and whether or not it should be used at all. The light blue spectrum in Figure 1 is the signal from some gravel under LUX, an underground dark matter experiment.
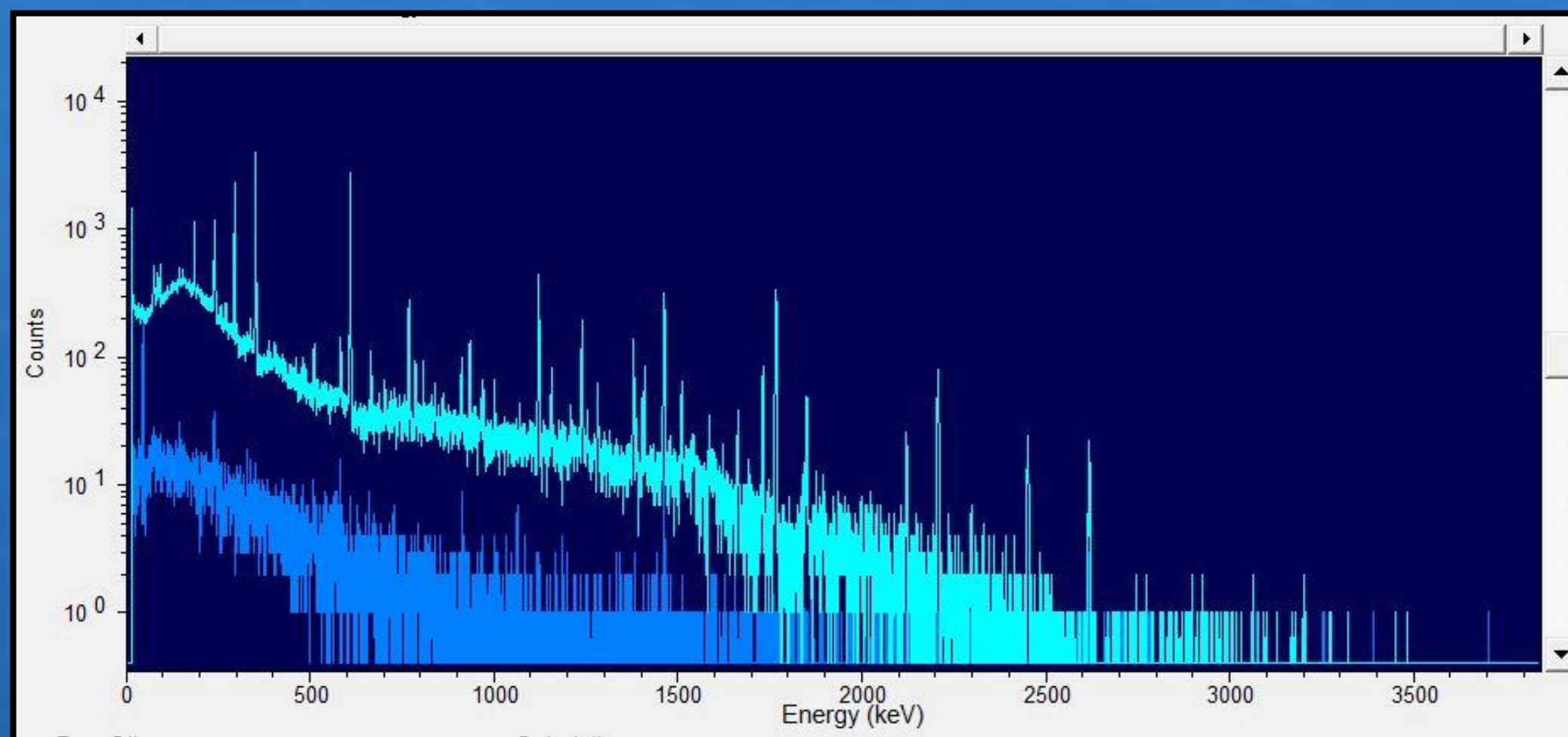

Figure 1. The spectrum from gravel (light blue) and the Ge detector's own background (dark blue).

Figure 2. Pieces of pipe around a HPGe detector.

High Purity Germanium Detectors (reference book)

At the Black Hills Underground Campus are set up four high purity germanium (HPGe) detectors in lead boxes or "castles" with Mylar covering, for the purpose of screening the materials to be used in the other experiments at the 4850' level of Sanford Lab. These detectors, like the one in Figure 2, are made of germanium, a natural semiconductor, because of how gamma rays interact with the matter they hit. If gammas were to strike any electrons out of their original positions in the germanium, they would become an imbalanced charge which could then be manipulated by an electric field for measuring purposes. Germanium is the best candidate for a semiconductor detector because it has a high enough atomic number to measure high energy gammas, allows displaced electrons (and the holes which they leave, which act as positive charges) to move easily through, and is available at high enough purity for a reasonable cost. [1]

Lead Stacking

Because germanium detectors are very sensitive and must measure very low-background materials, they are protected by lead shields. Lead blocks radiation, such as that emitted by the human researchers, very well and protects the integrity of the background generated by the material being measured. The easiest way to build such a shield is to stack lead bricks as tightly as possible (see Fig. 5) and in many layers around the germanium; because, however, lead itself is radioactive, what is used for the shield is centuries-old lead which has already undergone radioactive decay. In addition to lead, which comprises the greater part of the structure, copper also makes up an inner component of the shield, both in brick and in plate form, as seen below in Figure 3.
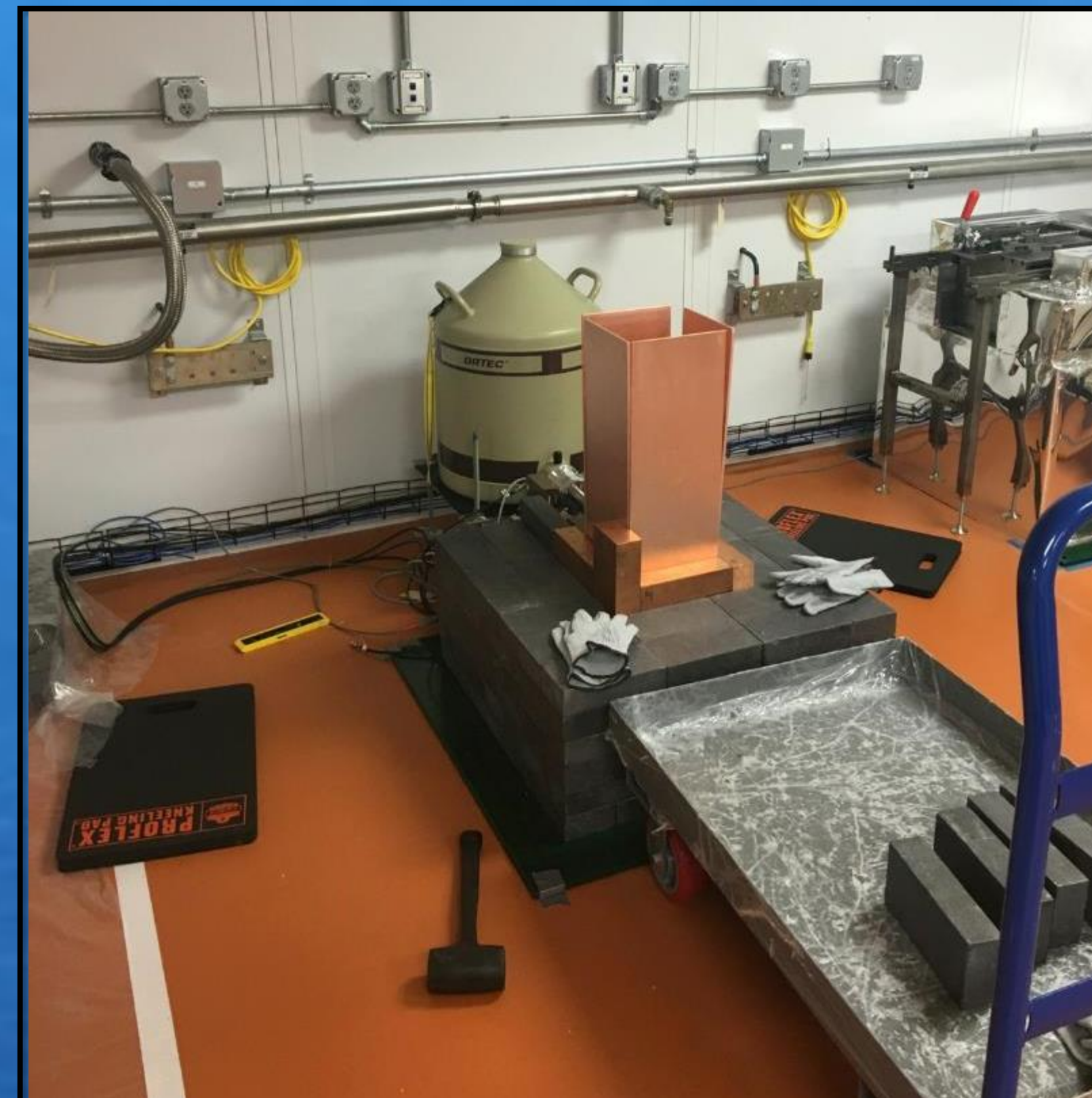

Figure 3. The base of the lead and copper shield for the detector Mordred.

Radon, Mylar, and the Purge

After the copper and lead are stacked around the germanium detector, the entire structure is wrapped in Mylar and taped securely, as shown in Figure 4 below. The reason for this final step is also related to reducing the background in the detector: radon emanating from the underground rock exists in the air and can decay, showing up in the signal. Because of the Mylar, the air in the detector is isolated from the surrounding environment; the chamber is flooded after sample changes with a nitrogen purge so the issue posed by radon-tainted air is no longer important. The lead bricks must be stacked tightly for the same reason, but if small gaps exist that radon will eventually decay (with a half-life of 3.8 days) and cease to be a factor.

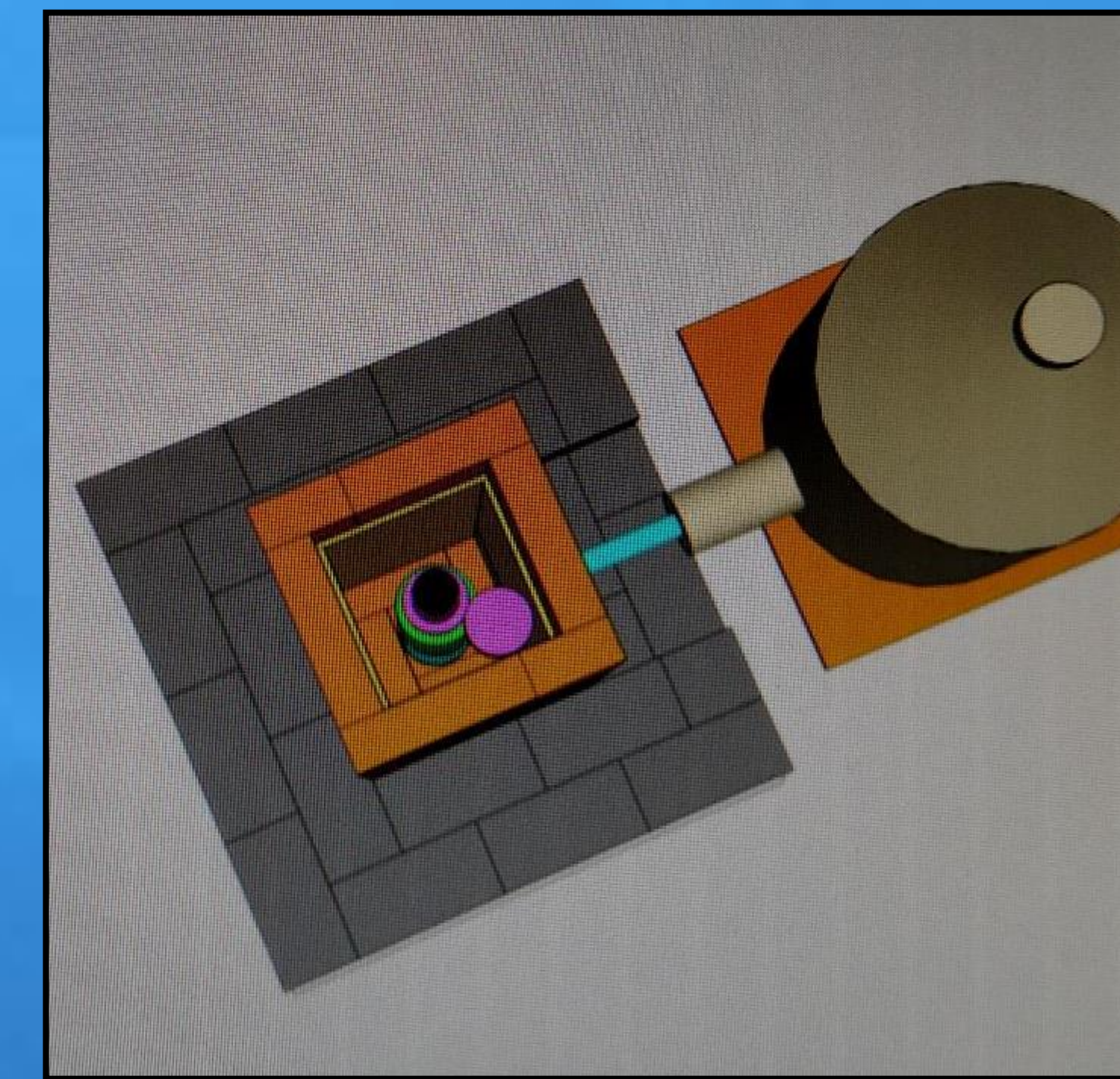Figure 4. The detector Solo being wrapped in Mylar.

Figure 5. A graphic showing a step of the lead stacking.

Geant4

Before a detector is built, researchers test its performance by means of a computer simulation designed using the program Geant4 [2,3], a set of tools developed by an international collaboration of physicists to model the passage of particles through matter. The simulations run by Geant4 are called Monte Carlo simulations because of the random number generators included in the toolkit. The program also contains details of various particle physics processes, such as the radioactive decay that the underground germanium detectors would be reading. The visualization feature, demonstrated in Figure 8, is especially useful for checking that the geometry programmed is the desired one, but can also show particle trajectories and hits in the virtual detector. These tests are currently being run for a new detector that will contain two germanium crystals instead of the usual one; this should be more sensitive than single crystal detectors, and the simulation hopes to determine if such increased sensitivity will require heavier shielding to eliminate the presumably larger background.


```
> mkdir geant4.10.2-build

> cd geant4.10.2-build

> cmake -DCMAKE_C_COMPILER=clang -DCMAKE_CXX_COMPILER=clang++
-DCMAKE_INSTALL_PREFIX=/Users/Physics/G4/geant4.10.2-install
-DGEANT4_INSTALL_DATA=ON -DGEANT4_BUILD_MULTITHREADED=ON
/Users/Physics/G4/geant4.10.02.p01

> make -j12

> sudo make install

> source /Users/Physics/G4/geant4.10.2-install/bin/geant4.sh

See also:
http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/InstallationGuide/html/
```

Figure 6. The Unix code for building Geant4.


```
physicsmac-bh:~ Physics$ cd G4/maeve-3/Run_EE33_rhyolite
physicsmac-bh:Run_EE33_rhyolite Physics$ ./ExecuteRun_EE33_rhyolite
Material is: rhyolite
Geometry is: EE33
./ExecuteRun_EE33_rhyolite: line 19: set_data: No such file or directory
[100%] Built target MAEVE
Processing file 1 of 1
Making a few heprep files
```

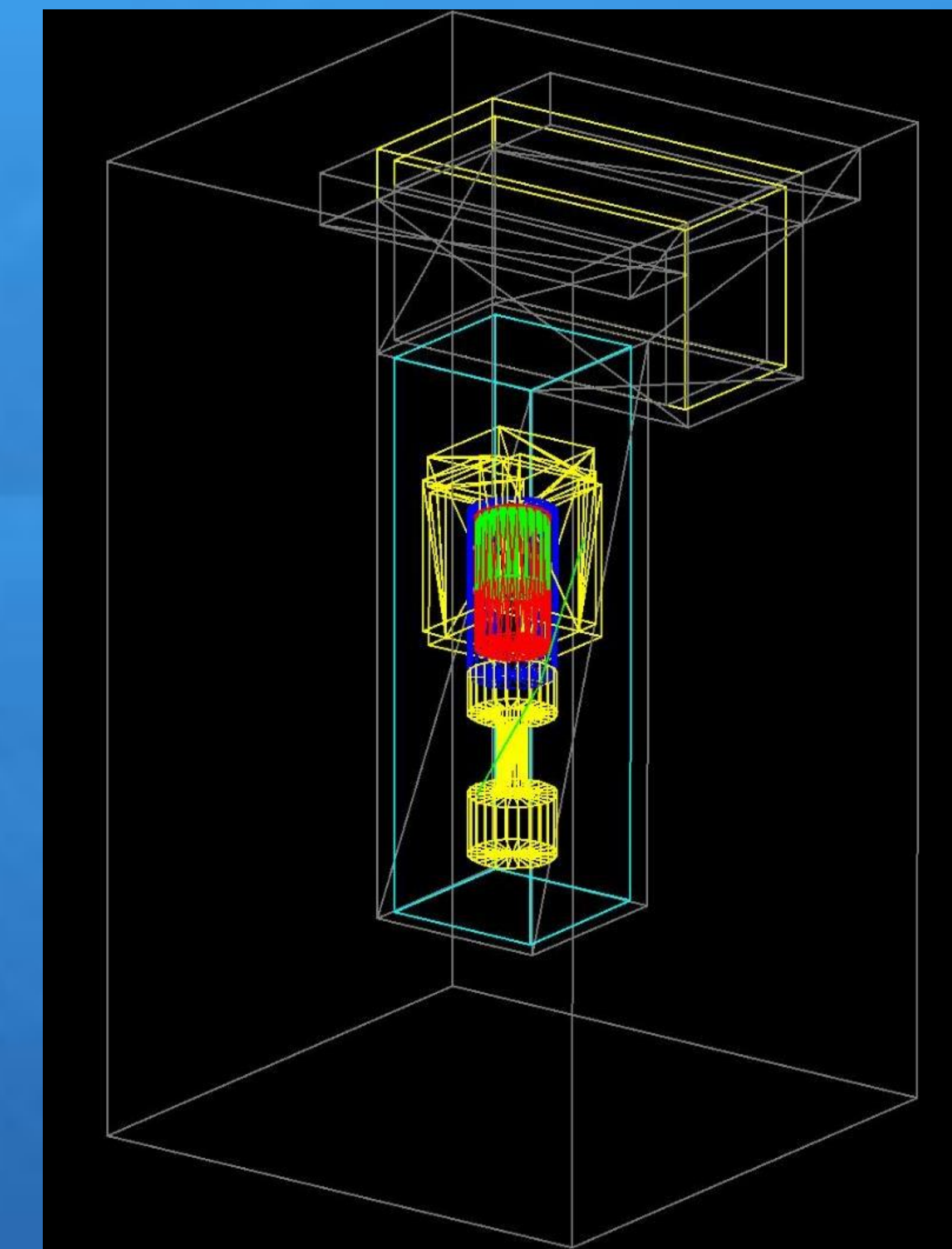Figure 7. A screenshot of the command line.

Figure 8. Geant4 model of an existing detector named Maeve.

Setting Up and Installing Geant4

The program Geant4 is notoriously difficult to install and get running, often taking as long as a week or two to work through numerous possible problems. If things go smoothly, the process is actually a fairly simple one, but rarely do things go smoothly. Downloading the source code is easy enough; before installation, however, there are several other programs and libraries which the computer needs to be able to install and run Geant4, including visualization tools and other programs for recording the data produced by the simulation. These include OpenGl [4] or Qt [5], X11 [6], Xerces-C++ [7], and others. If all these are properly installed, the programmer needs only to unpack the source code in the designated directory, create and move into a build directory, and then run the compile and make commands shown in Figure 6. There are various options for modes in which to run the program which may here be turned on, and certain options may require a compiler different from the default one.

For this work, I installed Geant4 and supporting programs on a 2013 Mac running OS X version 10.9.5. The computer has 12 cores, allowing Geant4 to operate in multi-threaded mode. This greatly improves the runtime of simulations. Figure 7 shows the commands and output of a simulation we were having trouble running.

REFERENCES
[1] Gilmore, G., & Hemingway, J. D. (1995). *Practical gamma-ray spectroscopy*. Chichester: Wiley.
[2] S. Agostinelli *et al.*, Geant4—a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A, Volume 506, Issue 3, 2003, pp. 250-303, ISSN 0168-9002, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.
[3] J. Allison *et al.*, "Geant4 developments and applications," in *IEEE Transactions on Nuclear Science*, vol. 53, no. 1, pp. 270-278, Feb. 2006. doi: 10.1109/TNS.2006.869826
[4] https://www.opengl.org/
[5] http://www.qt.io/download/#qt-lib
[6] https://www.xquartz.org/
[7] http://xerces.apache.org/xerces-c/download.cgi