Simulating Radioactive Decays in Next Generation Geoneutrino Detectors

Megan Geen
Wheaton College

Advisor: Nikolai Tolich

September 1, 2011

Abstract

From analyzing geological samples, the radioactive decays from the ^{238}U, ^{232}Th, and ^{40}K isotopes are believed to produce most of the Earth's internal energy. To confirm how much energy these three isotopes are producing, scientists can measure the number of anti-neutrinos (geoneutrinos) which are a product of these decays. Unlike old geoneutrino detectors, we are developing a new detector that takes advantage of total internal reflection to reduce the number of photomultiplier tubes needed and improve our ability to identify the particle type that reacted within the detector. Before building this detector, we want to minimize the amount of background events from radioactivity within the detector that look like anti-neutrinos. From simulations, we found that for the current design the background rate was almost 10^6 times larger than the geoneutrino rate. Therefore this work is the first step that allows us to consider other detector designs and particle identification systems that could decrease the background rate.

Introduction

The Earth's Heat Production

The Earth has a radius of about 6370 km and is made of 5 main layers. Humans live on the continental crust which is only 30 km thick on average. Using methods such as seismological and geological surveying, scientists are trying to understand the make-up and processes thsat are occurring within the Earth.

One process that scientist are particularly interested in is the Earth‘s total heat production. At about 2000 sites across the globe, scientists have drilled holes into the ground (the deepest being 20 km) and measured the temperature gradient inside. From this data, it has been extrapolated that the Earth produces 42 TW of heat.

Scientists now believe radiogenic decays from within the Earth can account for the Earth‘s large heat production. The main contributors to this theory are ^{238}U, ^{232}Th, and ^{40}K. All three of these isotopes have fairly large masses within the Earth. They also have long enough half-lives to be still decaying, but short enough to produce the energy needed. Current estimates from these decays put the Earths heat production at 19 TW. From models of mantle convection, radiogenic heat production should be a larger fraction of total heat dissipation and should be greater than 19 TW. Using a new detector design, we hope t o be able to directly measure the Earth‘s heat production from radiogenic decays by looking at the flux of anti-neutrinos produced by ^{238}U, ^{232}Th, and ^{40}K.

Anti-Neutrinos

Anti-neutrinos are the anti-matter counterpart to the neutrino. They come in three flavors (electron, muon, tau) like neutrinos. Anti-neutrinos that come from decays within the Earth are electron anti-neutrinos and are also called geoneutrinos. Electron anti-neutrinos are produced by beta decay:

$$n \rightarrow p + e^{-} + v_e$$

This is when a neutron within a nucleus decays into a daughter nucleus (proton) and an electron is released. An anti-neutrino is also produced to conserve lepton number.

The reason we use anti-neutrinos rather than the daughter nucleus or electron from this decay to measure the heat produced is that neutrinos are less reactive. When a beta decay occurs, the daughter nucleus and electron will travel only a short distance before interacting with another particle, but the anti-neutrino has the potential to travel thousands of kilometers before interacting. Therefore a geoneutrino produced within the Earth can travel to the crust and to our detector.

Because geoneutrinos are difficult to detect directly, we look for an inverse beta decay to identify an anti-neutrino. Inverse beta decays are described as:

$$v_e + p \rightarrow e^+ + n$$

An anti-neutrino interacts with a proton to produce a positron and a neutron. In our detectors, the positron almost immediately interacts with an electron to produce two 0.551 MeV gamma rays. About 200 ms later, the neutron will have lost enough energy to interact and cause an event that we can detect. This pattern of events 200 ms apart is the main way we determine an anti-neutrino interaction.

Methodology

Detector Design

The detector used is a grid of uniform rods as shown in Figure 1. Each rod consists of a thin acrylic container with a liquid scintillator center. Liquid scintillator is a man-made substance that creates light from charged particles. The amount of light created is proportional to the energy of the charged particle. At each end of each rod there is a single photomultiplier tube that detects the light. Between adjacent rods, there is an optically dense divider and an air gap on either side. During all simulations, each rod measured 0.202 m by 0.202 m by 8 m and were arranged in a 7 by 7 grid.

This detector design takes advantage of total internal reflection unlike previous detector designs. When a decay occurs within our detector and light is created from a charged particle, most of the created photons will stay in the same rod the reaction occurred within. Photons that hit the boundary between the liquid scintillator and air at an angle equal to or greater than the critical angle will travel down the length of the rod to one of our photomultiplier tubes. The photomultiplier tubes will count the number of photons that hit it which we can then use to analyze the particle that created this event.

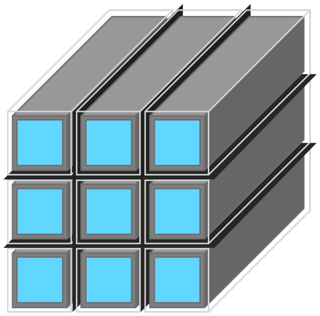


Figure 1: Detector made of 9 rods in a 3 by 3 grid

Patricle Reconstruction

For each particle we want to determine the original position along out rod, kinetic energy, and particle identification. To find the correction values for the position and energy reconstructions, we ran simulations for 1 MeV electrons.

To find the original position of a particle along a rod, we used the formula:

$$position = \frac{1}{2}\Big(\Delta t\Big)\Big(\frac{c}{n}\Big)\Big(\frac{1}{p_0}\Big)$$

where Δt is the difference in time between the photons that arrived at opposite photomultiplier tubes first, c is the speed of light in vacuum, n is the index of refractions of the liquid scintillator, and p_0 is the correction value. To obtain p_0, we ran simulations at 500 mm intervals along the length of the rod. We then graphed the original position vs the reconstructed position without p_0 and fitted a line through the points as shown in Figure 2. The slope of the fitted line is p_0, which was 1.05 in our detector.

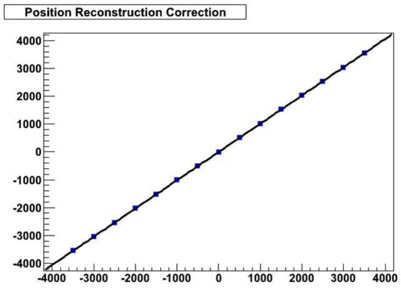


Figure 2: Position in vs Position out

Next we calculated the kinetic energy within a rod as:

$$KE = \frac{charge}{u}$$

where *charge* is the total number of photons that hit a photomultiplier tube within a rod and u is the correction value based on position. To get a formula for u, we graphed position vs charge and fitted a curve to it as shown in Figure 3. The formula we obtained from our simulations is $u = p_o + p_1(x^2) + p_2(x^4)$.

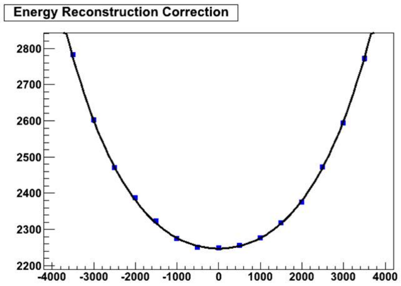
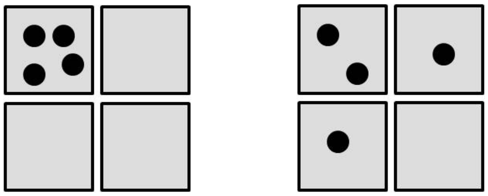


Figure 3: Position vs Charge

Lastly we want a particle identification which we define as:

$$ID = \frac{\textit{Highest KE in a Single Rod}}{\textit{Total KE}}$$

because depending on the particle type, kinetic energy will be found in 1 or more rods. Particles such as an electron or alpha particle lose their energy in a short distance in our detector. Other particles such as a gamma ray, lose their energy over a larger distance and will have kinetic energy in multiple tubes. Figure 4 provides an example for each of these cases.



(a) Alpha Particle, ID = 1 (b) Gamma Ray, ID = 0.5

Figure 4: Two examples of the particle ID where there are 4 rods and each dot is 0.25 MeV of KE making a total of 1 MeV KE in all 4 tubes.

Now we have a way of analyzing events in our detector, we want to determine the coincidence rate of decays from our detector materials that will look like an anti-neutrino. We can calculate this rate by:

$$CoincidenceRate = (DR)(NDC)(NDR)(TS)(E)$$

where DR is the the number of decays of ^{238}U, ^{232}Th, and ^{40}K per year from the materials used in our detector. These values can be found in Table 1. NDC is the number of atoms in the ^{238}U, ^{232}Th, and ^{40}K decay chains. ^{238}U has 14 atoms in its decay chain, 10 for ^{232}Th, and 1 for ^{40}K. NDR is the neutron detection rate which we set to 10 per second. TS is the length of time in which a decay from our detector material and a neutron have to occur within to look like an anti-neutrino. We set this value to 1 ms. E is the efficiency of our detector to distinguish a beta decay event from the detector‘s backgrounds. From our simulations we can determine the efficiencies of each in our detector.

Table 1: # of Decays in 1 Year

	^{238}**U**	^{232}**Th**	^{40}**K**
Gd Scintillator	1.99x10^{1}	2.86x10^{2}	2.93x10^{4}
Acrylic	1.77x10^{5}	5.76x10^{4}	7.65x10^{9}

Analysis and Results

Simulations were done individually for inverse beta decay, ^{238}U decay, ^{232}Th decay, and for ^{40}K decay. Each simulation consisted of 100 decays uniformly spread out within the center rod. Decays occurred either within the liquid scintillator or acrylic but not both at the same time.

Figure 5 shows results from the inverse beta decay in the scintillator. There are two distinct areas in the graph that represent the positrons (left cloud) and neutrons (right cloud). The gadolinium in our scintillator interacts with the neutrons producing high energy gammas. The other particles that could be in our detector will not have energy above 4 MeV. Therefore if we see an event with energy above 4 MeV, we can say that the particle that produced the event is a neutron.

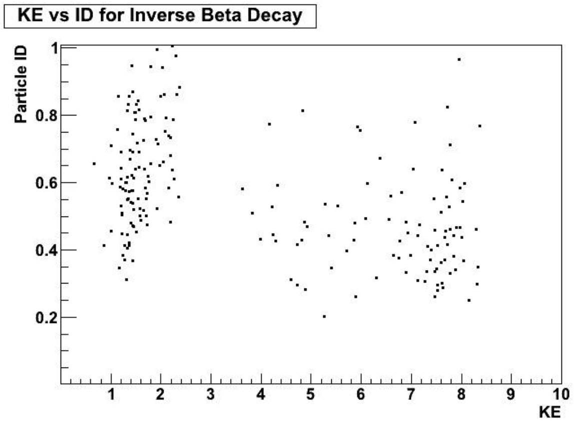


Figure 5: Kinetic Energy vs Particle ID from 100 inverse beta decays. The left cloud are positrons and the right cloud are neutrons.

Positrons are more difficult to identify than neutrons. From our simulation depicted in Figure 5, we can identify the region in which most positrons are located as below a particle ID of 0.91 and between 1 MeV and 3 MeV. Figure 6 both show the region in which the positrons should be located with ^{238}U, ^{232}Th, and ^{40}K backgrounds and the mentioned cuts applied.

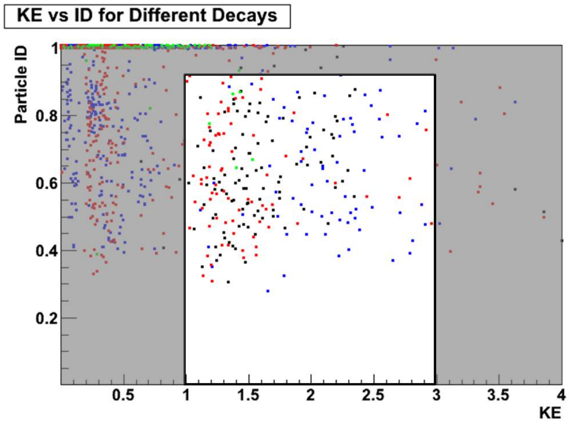


Figure 6: Kinetic Energy vs Particle ID with inverse

beta decay (black), ^{238}U decays (blue), ^{232}Th (red), and ^{40}K (green). Highlighted region is cuts performed on the backgrounds: 1MeV<KE<3MeV and ID<0.91

From this Figure you should notice that most of the ^{238}U, ^{232}Th, and ^{40}K is located below 1 MeV or has a particle ID of 1. These particles are low energy beta decays with a gamma associated, alpha particles, or electrons. With the mentions cuts, most of these are eliminated.

From Figure 6 we can determine the efficiency of our detector as :

$$ID = \frac{Events\ within\ the\ Cut}{Total\ Events}$$

For our detector we want the efficiency of identifying positrons caused by electron anti-neutrinos to be high while the efficiency of background decays to be low. Table 2 summarizes our results. In the gadolinium scintillator, all three types of backgrounds are below 10%, but in the acrylic ^{238}U and ^{232}Th rise to about 10% while ^{40}K stays about the same. With these efficiencies we can calculate the coincidence rates found in Table 3.

Table 2: Efficiencies

	ß$^{-}$	^{238}**U**	^{232}**Th**	^{40}**K**
Gd Scintillator	0.98	0.0489	0.0741	0.05
Acrylic	0.5	0.111	0.108	0.03

Conclusion

From previous experiments we expect to see approximately 50 anti-neutrinos from the Earth in a year. While the coincidence rates from the gadolinium scintillator are significant, the coincidence rates in the acrylic pose the greater problem being on the order of a million. It should be noted that the used neutron detection rate for these calculations is high compared to other experiments. By placing our detectors underground, this rate will be lowered by a factor of a thousand, immediately improving the coincidence rates. Unfortunately the acrylic will still be a problem due to its high ^{238}U, ^{232}Th, and ^{40}K concentrations that cannot be changed due to the current technology available today.

Table 3: Coincidence Rate in 1 Year

	^{238}**U**	^{232}**Th**	^{40}**K**
Gd Scintillator	1.91	2.12x10^{1}	1.47x10^{1}
Acrylic	3.11x10^{6}	5.36x10^{5}	2.29x10^{6}

In order to further reduce the coincidence rates future work on the particle identification should be done along with testing various dimensions for the detector. Other particle identification systems could include the 2nd or 3rd rods with the highest kinetic energy. Also the summation of kinetic energy in certain rods could prove to equal the kinetic energy of a specific particle we except to see. Different dimensions of rods could decrease the amount of acrylic used, or smaller rods could have more acrylic but improve the efficiency of the particle identification. Finally simulations must be done accounting for the build-up of certain isotopes in the ^{238}U and ^{232}Th decay chains and interactions with carbon that can also look like anti-neutrinos.

References

[1] Nikolai Tolich, *Experimental Study of Terrestrial Electron Anti-Neutrinos with KamLAND.* Stanford University, 2005.

[2] Enomoto Sanshiro, *Neutrino Geophysics and Observation of Geo-Neutrinos at KamLAND*, Tohoku University, 2005.

[3] William R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer, 1994.