# Monte Carlo Simulations for Future Geoneutrino Detectors

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## Abstract

*The main contribution of heat in the earth's mantle is thought to be the radioactive decays of $^{238}U$, $^{232}Th$, and $^{40}K$. A precise measurement of the levels of $^{238}U$ and $^{232}Th$ can be determined by measuring the flux of $\bar{\nu}_e$ (geoneutrinos) emitted from their decay chains. Although detectors such as kamLAND and Borexino have detected few geoneutrinos, a new cost effective geoneutrino detector is proposed which takes advantage of the total internal reflection within a long rectangular prism acrylic container of liquid scintillator having a single photomultiplier tube (PMT) on each end. An array of these containers would allow for a large scintillator volume relative to the number of PMTs, but a design with such a large ratio of arcylic to scintillator may suffer from a larger background from naturally occurring $^{238}U$ and $^{232}Th$ within the acrylic. The event signatures of these decays were compared to those from neutrino interactions using RAT, a Monte Carlo simulation software based upon GEANT4. In this paper I will discuss the limitations which arise from this design such as, the thickness of the acrylic container which causes high loss of optical photons due to scattering and absorption, rod length which results in higher scattering rates within the scintillator, and size of the array.*

## 1 Introduction

From sampling experiments done in various locations, on average the earth is dissipating about 44.2 TW of heat from the combined loss in the oceanic and continental crusts[1]. Thermodynamic models suggest that, after taking into account the continental crust heat production, the earth is dissipating heat at a rate of 37.7 TW. Current Urey Ratio estimates set the lower limit to 0.69 based upon mantle convection and premoridial heat. Thus the earth must be producing heat at a rate of 26TW. The most likely producer of this mantle heating would be radiogenic heat from the $^{238}U$, $^{232}Th$, and $^{40}K$ decay series'.

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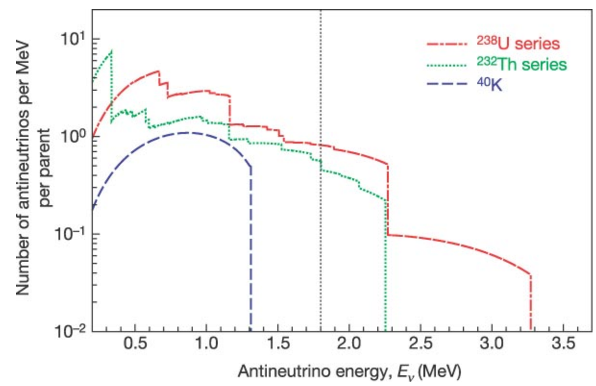


Figure 1: $\bar{\nu}_e$ energy spectrum for the $^{238}U$, $^{232}Th$, and $^{40}K$ decay series. The dotted vertical line at 1.8 MeV represents the energy threshold for an $\bar{\nu}_e$ to capture on a $p^+$ [equation 1].

Since direct measurement is difficult to do, current estimates based upon geological sampling estimates the heat production from radiogenic decays to account for only 19 TW. However in order to justify these predictions, direct measurements of the $^{238}U$ and $^{232}Th$ are required. One method for determining the amount of radiogenic heat being produced within the mantle is by directly measuring the flux of $\bar{\nu}_e$ being emmitted by $\beta^-$ decays in the decay series for $^{238}U$, $^{232}Th$, and $^{40}K$. The $\beta^-$ decay is a three body decay, and as a result won't produce energy peaks for the decays products, but instead will have a widely distributed energy spectrum[Figure 1]. Since the $\bar{\nu}_e$ only interacts weakly it can pass through the earth relatively undisturbed with an extremely small probability of interacting with matter. Thus by measuring the flux of $\bar{\nu}_e$ coming from the earth, we can measure the total number of $\beta^-$ decays occurring within the mantle, and therefore the heat production rate due to these isotopes.

## 2 Detection

The three decay chains shown in figure 12 show which decays within the three decays series' are $\beta^-$ decays, and thus will emit an $\bar{\nu}_e$. These $\bar{\nu}_e$ will be detected

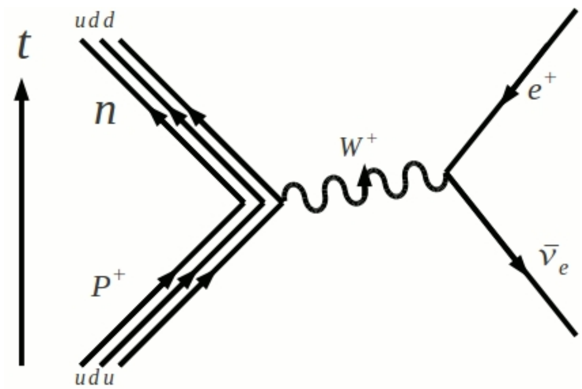


Figure 2: Charged current interaction: $\bar{\nu}_e$ interacts with a $p^+$ producing a $n$ and $e^+$

through the charged current interaction within a liquid scintillator detector. As shown in figure 2 the $\bar{\nu}_e$ will interact with a $p^+$ producing a $n$ and and a $e^+$.

$$\bar{\nu}_e + p^+ \rightarrow n + e^+ \quad (1)$$

The liquid scintillator will produce optical range photons (scintillation light) whenever a charged particle propagates through it. This means that the $\bar{\nu}_e$ can't be detected by it, but the $e^+$ product from the charged current interaction will produce scintillation light. The $e^+$ will annihilate with an $e^-$ soon after its production producing two 0.511 MeV $\gamma$. The $\gamma$ will Compton scatter off of $e^-$ within the scintillator transferring their momentum to the $e^-$, producing more scintillation light. The scintillator is doped with Gd which the $n$ from the charged current interaction will capture on within a very defined time window of about 30 $\mu s$. This $n$ capture will emit two more $\gamma$ with a total energy of 8 MeV and can be detected as a coincidence event to help identify the charged current interaction. Any event that occurs without this coincidence time window will thus be vetoed.

$$m_n + m_{e^+} - m_{p^+} \approx 1.8 MeV/c^2 \quad (2)$$

The minimum $\bar{\nu}_e$ energy to cause the charged current reaction can be calculated from equation 2. This energy threshold is at about 1.8 MeV and is represented in figure 1 by the vertical dotted line. This threshold is beyond the maximum $\bar{\nu}_e$ energy for the decay of $^{40}K \rightarrow Ca^{40}$ which rules out any detection of $^{40}K$ using the charged current interaction. From figure 1 it's clear to see that the $^{238}U$ and $^{232}Th$ series have $\bar{\nu}_e$s which are beyond the threshold energy and thus can be detected via the charged current interaction within the liquid scintillator

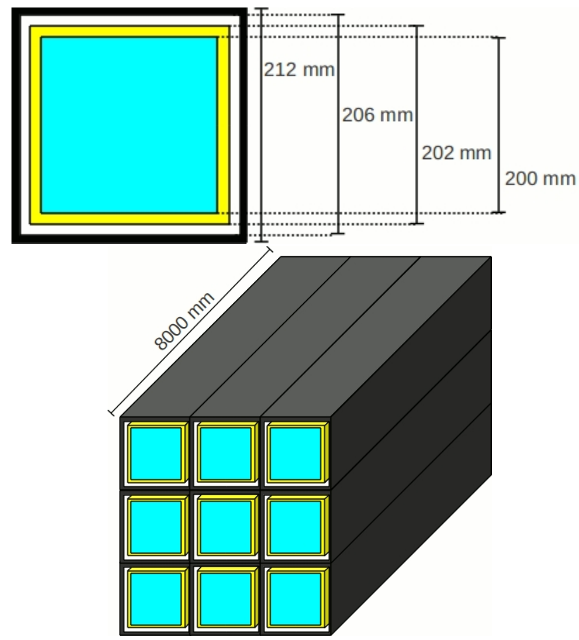


Figure 3: Liquid scintillator geoneutrino detector: Liquid scintillator inner region, surrounded by a reflective acrylic, air, then an optically thick acrylic

## 3 Detector

Previous experiments, such as KamLAND have been able to detect these geoneutrinos but with high levels of reactor background due to detector location [1]. In order to make more accurate measurements with a high event rate, a new detector is proposed which will be placed in a location far from nuclear reactors and other sources of background signal. This detector (shown in figure 3 will be composed of an array of scintillator rods which can be assembled and transported individually in order to reduce construction and development costs. Each rod will be composed of an outer layer of an optically thick acrylic which will act as a barrier for optical photons escaping into surrounding rods while allowing for $\gamma$ to pass straight through. This will help to keep events that produce only charged particles such as electrons to stay within a single rod, while $e^+$s can be detected as an event within multiple rods due to $\gamma$ from the annihilation scattering. Within the optically thick acrylic will be a reflective acrylic container holding the liquid scintillator with a boundary between the two acrylics of air, allowing for a ratio between the index of refraction of the acrylic to the air of 1.509. This will help to propagate the scintillation light from an event to the ends of the rods. On each rod end there will be

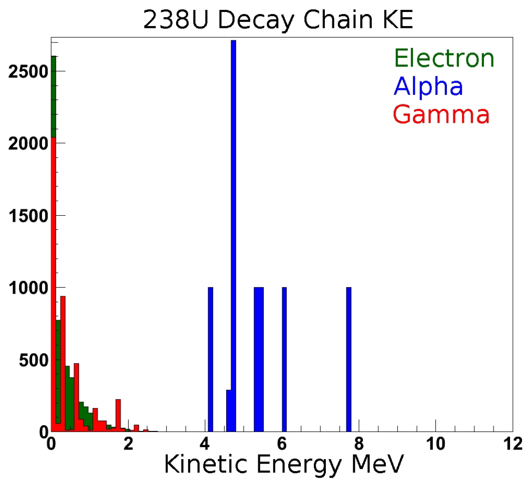


Figure 4: Histogram of the kinetic energy in a Monte Carlo simulation of the $^{238}U$ decay series

placed a single photomultiplier tube (PMT) that will detect the scintillation light within the tube.

## 4 Background Signal

Since the number of events for neutrinos will be very low, it's very important to be able to identify and eliminate as much background as possible. The coincidence event will help in doing this very well, but there is still a chance of random coincidence occurring if a neutron from background happens to capture just after some background in the right energy regime occurs. A leading background looked at in this paper is that from naturally occurring decays from the $^{238}U$ and $^{232}Th$ decay series' within the scintillator and acrylic. The events from these types of background won't just be the $\beta^-$ decays, but also the alpha decays which can show up as a signal in the PMTs. Plotted in figures 4 and 5 are the Monte Carlo kinetic energy distributions for the $^{232}Th$ and $^{238}U$ decay series'. Since the alpha particles are very large, they will be quenched very quickly by a factor of about 10 20 compared to an electron with a similar energy. The electrons however can produce a significant amount of light within a single tube, and the $\gamma$'s can produce events within multiple tubes. This signal combined with a random neutron capture would end up being detected as a $\bar{\nu}_e$ event. Thus elimination of this background would help to prevent false $\bar{\nu}_e$ events from being detected.

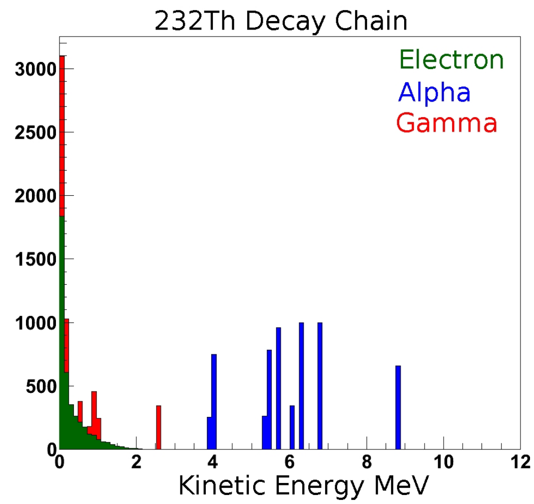


Figure 5: Histogram of the kinetic energy in a Monte Carlo simulation of the $^{232}Th$ decay series

## 5 Monte Carlo Calibration

The detector itself can only measure two specific parameters. These are the amount of charge that is collected on each PMT within an event window, and the time at which this collection began. In order to get any meaningful information out of these two it was necessary to first calibrate how each of these looks for known events within the Monte Carlo.

The first calibration made was the location dependence of an event on the light seen by the PMT. Due to absorption probabilities and scattering within the liquid scintillator by the scintillation light, the amount of light gathered by the PMT was strongly associated with where the event occurred. Figure 6 shows the total number of photons collected by two PMTs as a function of event position for a 1 MeV electron. This electron is then used as the standard of measurement for the energy of an event. Without any real physical motivation, this graph was fitted with the function:

$$Photons = (\frac{x}{390})^2 - (\frac{x}{410})^{\frac{3}{2}} + (\frac{x}{3000})^{12} + 107.5 \quad (3)$$

The function produces an accurate fit for the position dependence.

The second calibration made was on the amount of charge picked up by a PMT whenever a single photon would hit. When a PMT is hit, it knocks out a photoelectron which then propagates into the PMT sending a cascade of electrons to the detector which is detected as a total charge. This means that the PMT doesn't

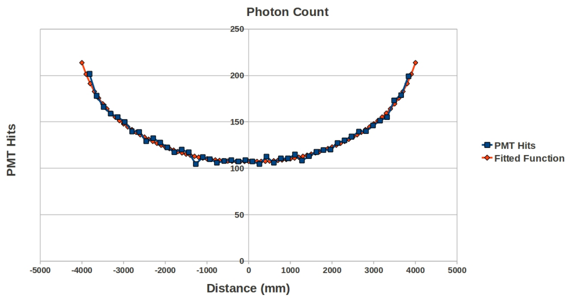


Figure 6: The position dependence on the photon count for an event within an 8m liquid scintillator tube fitted by equation 3

necessarily count the number of photons that hit it, but rather the amount of charge deposited by those photons which is a Poisson distribution about the true value. In order to determine a good mean value with a small width poisson distribution, a Monte Carlo simulation was done that involved sending 1000 photons into a single PMT at once over 7000 events. Figure 7 shows the results of this normalized to a single photon. From this data, it is determined that the average charge per photon is around 29.74.

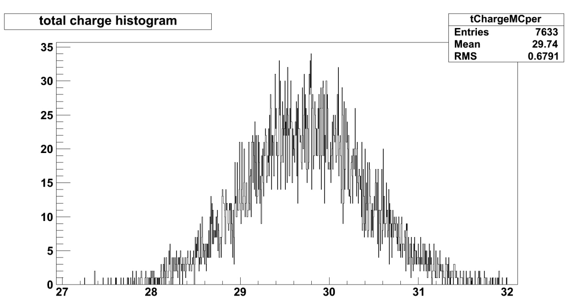


Figure 7: Total charge on a single PMT from 1000 photons, normalized to a single photon. Charge from a single photon has a mean value of 29.74, and an RMS of 0.6791.

## 6 Event Reconstruction

After having the calibration data, the position and energy of an event within the detector can be reconstructed. Two assumptions are made in order to recalculate the position of an event. First, we assume that whenever an event happens, the scintillation light that is produced is isotropic and is plentiful enough that there is good probability of one photon traveling in the direction of each PMT. Second, the first photons that hit the PMTs travelled in a straight path to do so. The first assumption is pretty good for higher energy events, but creates large uncertainties in events that only produce a few photons. The second assumption works well over short distances and with higher energies, but will lose efficiency when traveling the entire length of the detector. The position is then calculated by measuring the difference in the first and second PMT hit and using the following formula.

$$Position = \frac{\Delta tc}{2n} \quad (4)$$

Where $\Delta t$ is the difference in time, $c$ is the speed of light in a vacuum, and $n$ is the refractive index of the scintillator ($n = 1.505$). Figure 8 gives a basic picture of the reconstruction.

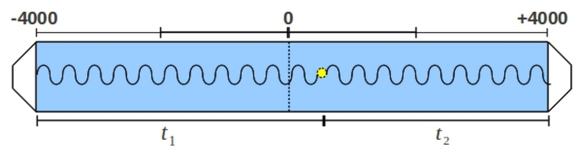


Figure 8: Representation of the position reconstruction of an event within a single rod of liquid scintillator

Once the position of an event is known, the energy of the event can be reconstructed using the position, charge, and the two calibration parameters.

$$Energy = \frac{Charge}{P * C} \quad (5)$$

Where the Charge is the total charge measured by all of the PMTs for a single event, P is the number of photons produced by a 1 MeV electron at the position of the event (according to equation 3), and C is the charge of a single photon as determined from figure 7. Using this formula, Monte Carlo runs were done with 1000 $e^+$ events at 0.5 MeV, 1000 $^{238}U$ decay chains, and 1000 $^{232}Th$ decay chains placed randomly within the central tube of a 9 by 9 array. The energy reconstruction is plotted in figures 9 and 10. There is a very clear window of measurement for the $e^+$s where some of the decay events overlap and thus would be detected as $\bar{\nu}_e$'s in the detector.

## 7 Data Filter

Using the information from the simulation, cuts to the data could be made that would allow for a reduction in background with minimal effect to the event count. The easiest cut to make was to the energy since, as shown previously, there is only a small portion of the

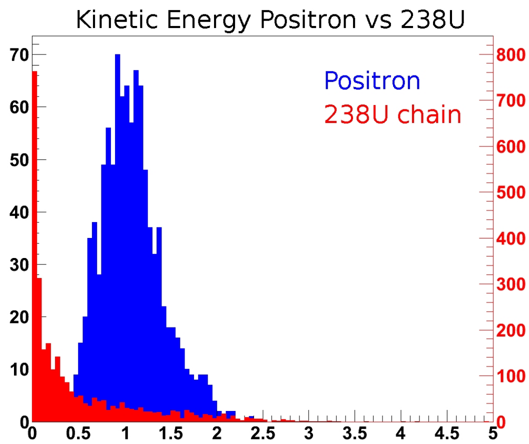


Figure 9: The reconstructed energy of 0.5 MeV positron events, plotted against the reconstructed distribution of energies from the $^{238}U$ decay series

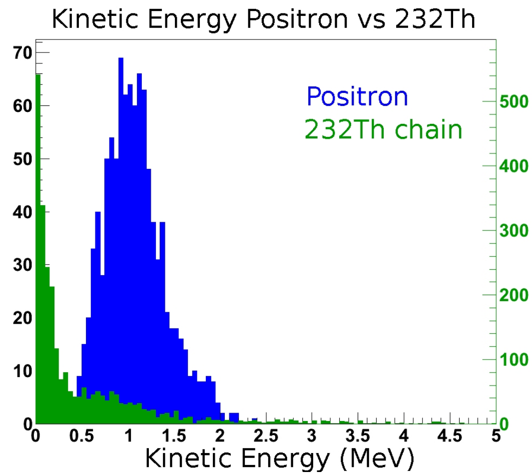


Figure 10: The reconstructed energy of 0.5 MeV positron events, plotted against the reconstructed distribution of energies from the $^{232}Th$ decay series

backgroung that is within the signal window. The events of interest then would have to fill the requirement that they were between 0.5 MeV and 2.0 MeV (The $e^+$ annihilation causes the lower bound to not be 0). The next cut relied on the fact that $\gamma$ from the annihilation would cause the event to be spread to mulitple tubes rather than a single tube. A charge filter parameter, described by equation 6, takes advantage of this fact to seperate the events further.

$$ChargeFilter = \frac{MaxCharge}{TotalCharge} \qquad (6)$$

Where the $MaxCharge$ is the total charge of the tube with the highest combined charge from both of its PMTs, and the $TotalCharge$ is the charge over all of the PMTs combined. Figure 11 shows the results of these two cuts applied together.

## 8 Conclusion

From the results of the reconstructed energy, and the applied filters, the Monte Carlo simulation shows that a detector of this design would be able to eliminate about 93% of the $^{238}U$ background signal, and about 86% of the $^{232}Th$ background signal. The cut would cause some loss to the total number of events seen since this cut also causes a loss of about 36% of the $e^+$ hits.

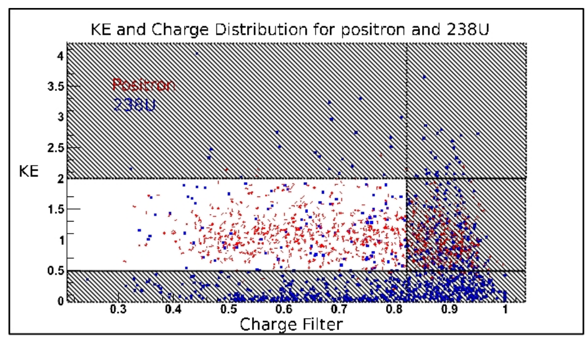


Figure 11: Kinetic energy of the $e^+$ and $^{238}U$ plotted against the ChargeFilter (equation 6). The Shaded out region represents the cut areas chosen to eliminate a large percentage of the $^{238}U$ without greatly reducing the $e^+$ count.

## References


[1] Tolich, N. R., “Experimental Study of Terrestrial Electron Anti-neutrinos with KamLAND,” pp. 1-14, 3/05

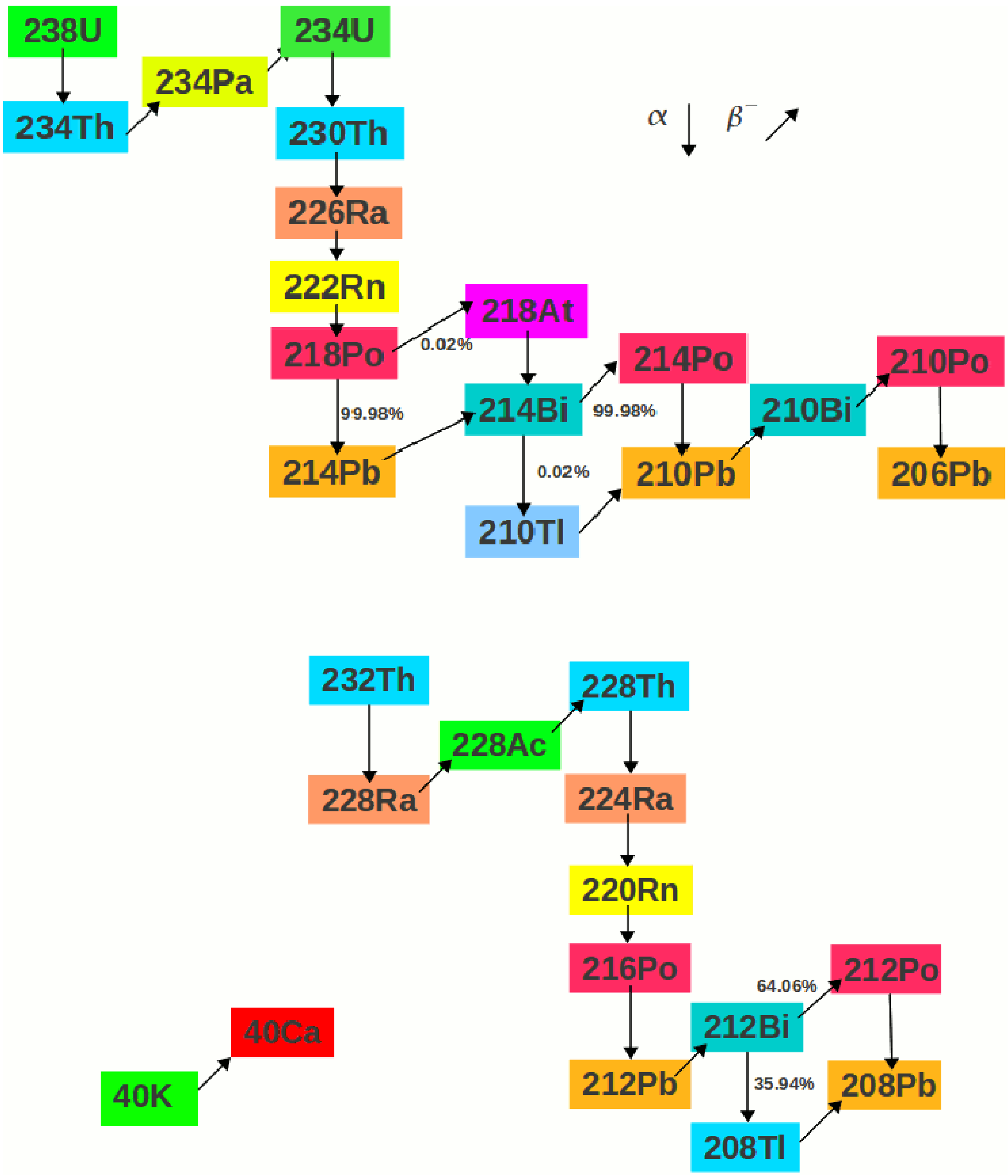


Figure 12: Decays chains for $^{238}U$, $^{232}Th$, and $^{40}K$