

# GRIDS 2018

## BiPo Low level radiation Counting

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Note: The BiPo laboratory is expected to take about 3 hours total. Hence we will normally start at around 10:30, and end at around 2:30, with an hour in the middle for lunch. On days when there are two groups doing the lab, the second group will start at 2:30. Students can be prepared by reading some of the material in advance, where possible.

# 1 Introduction

Experiments searching for rare events have to have exquisite control of backgrounds to ensure that these do not either overwhelm the rare signal events, or fool the experimenter into thinking they have found a signal which was really caused by a background signal that can't be discriminated from the true signal. To avoid such background issues, experiments work hard to:

- Reduce backgrounds to ultra-low levels,
- Determine methods to discriminate between signal and any residual backgrounds,
- Find alternate methods of reliably quantifying the amount of background present.

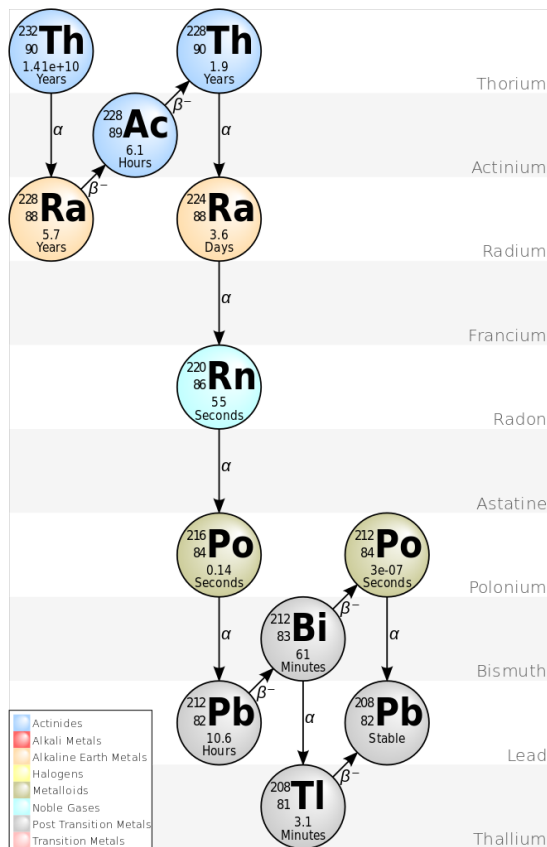
The BiPo method is a very particular tool used to measure the amount of Uranium or Thorium in various samples of interest to the experimentalists. Why these? It turns out that both Th and U (as well as  $^{40}\text{K}$  have life times long comparable to the age of the earth so by know they are found in almost all materials, at some level. As they are radioactive, the decay products may interfere with experimental results. These products are problematic in almost all low background searches.

Figure 1 shows the decay sequences for  $^{238}\text{Th}$  and  $^{232}\text{U}$ . Note that the life time of the parent nuclei are billions of years in length, and hence comparable to the age of the earth. Also note that all other half lives are relatively short. The problem with these decays in so far as rare event searches are concerned is as follows:

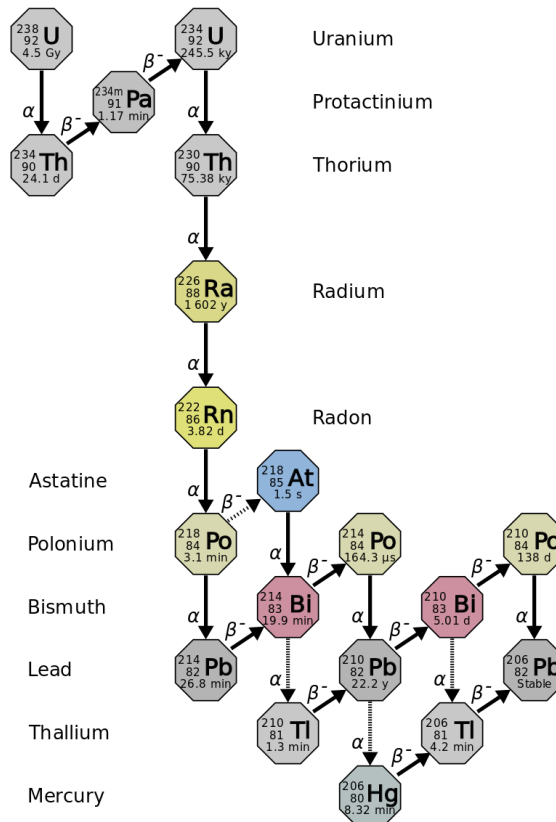
- Unless you are planning a very long thesis, there is no way to wait for the radioactivity to “die down”. As long as the parent material is present, the rest will be there, usually in secular equilibrium.
- There are numerous  $\alpha$ , and  $\beta$  -decays in each chain, and as well, the decays will often be to excited states of the daughter nuclei, with the subsequent emission of  $\gamma$  rays.
- Radon is a particular problem, especially for the Uranium chain (where the half life is 4 days). This is because radon is a gas that can get diffuse or emanate out of one material, and migrate into your detector. It is less of a problem in the Th chain as the one minute half live limits its mobility.
- It is difficult to control the amount of U and Th that gets into steel and similar construction elements, unless you are working with the company during the smelting and work with them to achieve lower impurities through some filtration of U and Th at that time, and for all components in your detector.
- You may also need to protect your detector components from exposure to air to the degree possible. This is because of the long lived  $^{210}\text{Pb}$  near the end of the U chain. Radon decays in the air produce daughters, including  $^{210}\text{Pb}$  which settle onto the surfaces of your detector and become embedded there as the daughter nuclei recoil into the surface. With a half life of 22 years, these persist over the life time of the experiment.

Some questions to ponder:

- ◆ What is secular equilibrium?



(a)  $^{238}\text{Th}$  Decay Chain



(b)  $^{232}\text{U}$  Decay Chain

Figure 1: The decay chains for the ubiquitous  $^{238}\text{Th}$  and  $^{232}\text{U}$ . (Images from Wiki Commons at: [https://en.wikipedia.org/wiki/Decay\\_chain](https://en.wikipedia.org/wiki/Decay_chain) ).

- ◆ If the sample is in secular equilibrium how will the decay rate of a long lived isotope in the chain compare with one that is very short lived?
- ◆ What does this say about the amount of each isotope in the sample, and hence if you are making a measurement (for example using mass spectroscopy) which counts the number of individual nuclei for each isotope, will you get a better sensitivity measuring the long lived isotope or the short lived one?

How does the BiPo method work? You will notice that at the end of each of the Th and U chains there is a branch with a Bismuth decay (Bi) followed by a Polonium decay (Po). This sequence is the “BiPo”. In each case the decay of the Bi produces a  $\beta$  particle, and the decay of the Po produces an  $\alpha$  particle. Hence if you could detect a  $\beta$  followed by an  $\alpha$  then this would be a tell tell sign that you were seeing events from Th or U. Such coincidences are difficult to see, unless they come in quick succession, other wise they appear with random time correlation.

Fortunately; in the Th chain, the decay:  $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$  gives a  $\beta$  and  $\alpha$  separated by a short time interval (the decay time of the Po is 300 ns).

Likewise in the U chain, for  $^{214}\text{Bi} \rightarrow ^{214}\text{Po}$ , the lifetime of the Po is 164  $\mu\text{s}$ . while not as close in time,

it can still work if the activity is low enough.

Hence the general idea of this technique is to identify Th and U depending on whether or not there is a coincidence with decays separated by about 300 ns, or 164  $\mu$ s. (Keeping in mind of course that these are exponential decays with a mean life  $\tau$ ).

## 2 The SNO example

One of the ways the SNO experiment could detect any flavour of neutrino was through the reaction:

$$\nu_x + d \rightarrow n + p + \nu_x$$

which can occur provided the incoming neutrino has an energy above the binding energy of the deuteron (2.2 MeV). SNO then detected the neutrons released in the interaction. A major background source would come from the photo-disintegration of the deuteron:

$$\gamma + d \rightarrow n + p$$

From a detector perspective (seeing only the neutrons) these two reactions are indistinguishable. Hence it was important for SNO to not have any sources of photons with an energy above 2.2 MeV.

However, in the decay of  $^{208}\text{Tl}$ , a photon with an energy of 2.6 MeV is emitted, as shown in figure 2.

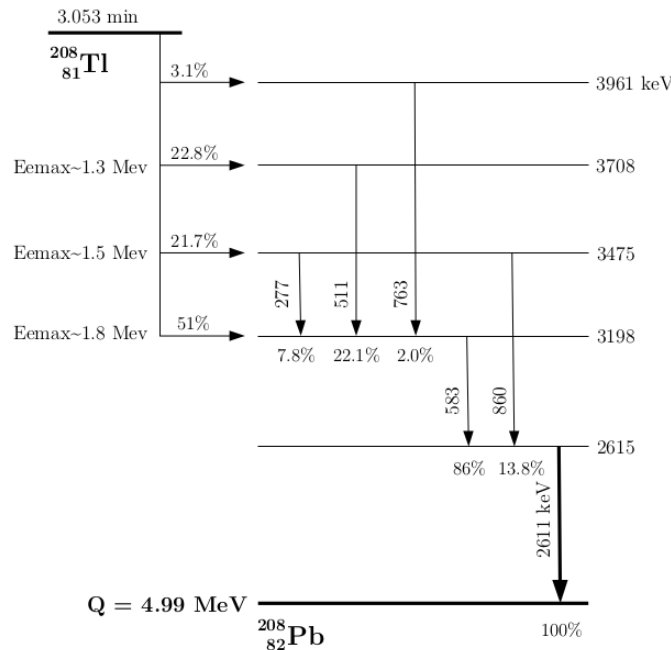


Figure 2: The decay scheme for  $^{208}\text{Tl}$ . Note that in 100% of the cases, a photon of energy 2.611 MeV is released. These are a potential problem for SNO if there are any Th or U contaminants (there is a similar problem in the U chain with high energy photons emitted in the decay of  $^{214}\text{Bi}$ ).

In the SNO experiment we worked incredibly hard to remove all of the U and Th, and their daughters like  $^{228}\text{Th}$  and  $^{226}\text{Ra}$  which are relatively long lived. Then at the end of all that work we had to

measure the tiny residual very accurately to know that the “neutrino” events we were seeing could not be from photo-disintegration. This was done as follows:

- Pass about 500 tonnes of heavy water from the detector over an ion exchange material that collects Th and Ra with a high efficiency. This takes about a week.
- At the end of the week, bring that column loaded with ion exchange to surface.
- Now remove all the Th and Ra with about 15 liters of strong acid.
- Neutralize the acid, and pass it over a very tiny column, to again extract the Ra and Th.
- Now wash that tiny column with acid. At this point you have about 15 cc of acid, which contains most of the Th and Ra that was originally in about 500 tonnes of SNO heavy water.
- To measure the amount of Th and Bi, we mix the 15 cc of acid into a liquid scintillator especially designed to be able to mix with about 1 part in 4 of an aqueous solution.
- Then, one simply looked for  $\beta \alpha$  coincidences producing light in the scintillator cocktail.

### 3 Apparatus

The apparatus is quite simple, and largely prepared. At least it worked a few weeks ago when it was tested.

The basic element is a counting pot which gets filled with liquid scintillator, and has mixed into it a water based solution miscible in the liquid scintillator. The water to scintillator ratio should not be more than 1:4, and usually 1:5 or so is better.

The scintillator pot is then mounted on top of a PMT, which produces a signal for every decay. The output signal is fed into a set of electronics which can count the number of coincidences.

This PMT works best at a voltage of around 1100 V. Note: the PMT is always kept inside the copper shielding pot, and kept light tight.

**If the lid is ever removed with the PMT turned on, that PMT is gone forever, the experiment is over, and that student is buying beers for everybody else that night. Always turn off the HV before opening the pot!**

In an ideal world, the students would work out the electronics themselves, as it is a good learning experience to set up the logic, and learn how to adjust it. However, these modules were old when I was using them as a graduate student, some decades ago, and they haven’t improved with age. There are a number of flaky channels, and it is a bit finicky to get it all to work. This is why I am hoping it still works after sitting there a few weeks.

So your first job will be to reverse engineer the electronics a bit, and make a logic diagram of the setup that you can understand and adjust.

## 4 Instructions/Ideas

As mentioned above, the first step will be to reverse engineer the electronics to understand the circuitry. Remember, the purpose of the electronics is to count the number of coincidences separated in time. Here are some questions to explore:

- Is this the logic you would have used in setting up the circuit? If not, can you imagine a reason for the more complicated circuitry?
- What is the purpose of all the 50 ohm terminators?
- In a typical timing experiment one would prefer to use constant fraction discriminators. How do these work, and why can we use non CFD for this measurement?
- Is this setup optimized for detecting Th or U?

### 4.1 Safety

- The PMT operates at about 1100V of high voltage. Do not tamper with the HV cables, or the signal cable to the PMT. Due to the unusual (not particularly clever) design of the base, both the signal and HV cable are lemo cables. Not only does this introduce personal risk if you were to make/break connections under a load, but likely you would also destroy the PMT if you interchanged these. (See section above about how many beers that will cost you, if you survive).
- The liquid scintillator, while not particularly toxic, is not good for you, and you should avoid contact with it.
- If exposed to ambient light under load, the photocathode will evaporate, and the PMT will be a paperweight.

### 4.2 Things to try

You should start with the “radioactive” sample already prepared. This was made by taking a typical welding rod (known to have a trace of Th included), and smashing it to bits. The bits were then soaked in acid, hoping they would leach some of the Th from the rod, and get them into solution. Some of the acid was then added to scintillator, and a sample was borne.

- Before putting the sample on the PMT. Check/double-check that the power is off.
- Use a smidgen of optical grease to mount the sample to the PMT. It is best to daub this on with the end of a screwdriver. This is the time honoured technique.
- Place the cap on, and light seal the copper pot with some black electrical tape.
- Connect the scope to a signal channel using a spare output in the electronics, and bring up the voltage while watching the scope. Do the signals look good?

- If not there already, move the scope to an analogue signal and check that the threshold looks about right by comparing the value set on the discriminator to what you see for the raw signal on the scope. Ideally the threshold is set to be just above the noise from the PMT and electronics. You could make a plateau curve if you like.
- Have you got the scope impedance correct? What happens to the signals if you have it wrong? What if some 50 ohm terminators are removed?
- Connect the scope to the two inputs to the coincidence unit, and convince yourself the timing is set up correctly. Do you think you can see any Th coincidences by eye? If there are  $\alpha$  and  $\beta$  in the scintillator, is there some way to tell which is which? The answer may not be as simple as you first think. If so, does the ordering of signals on the scope look right?
- How could you tell if you are seeing coincidences from Th, or just random coincidences from a high rate of decays from the entire decay sequence, in the scintillator? Take the data you need to estimate this. You should be able to predict the coincidence rate from one measurement, and also verify the presence of Thorium in the sample by measuring the lifetime.
- How could you measure the inherent background rate of scintillator, radon in the air, muons, electronics... try it if you like. Can you see a difference in absolute and coincidence rates compared to the hot sample?

You may wish to try other samples. Coffee is pretty radioactive, but may make the scintillator opaque. Can you think of any other samples you might try? Leaves from blueberry plants would be good to try, if you happen to have some.

### 4.3 Analysis

The instructions above were purposely sparse. While the instructor is always present to guide you, see how much you can explore on your own with the information in this manual. Things you might try for the analysis:

1. Can you confirm that there was Thorium in the prepared sample? How well do your measurements compare with expectations?
2. You probably observed a fairly high rate. What is the likelihood that the coincidences are just random ? Can you calculate this?
3. Do you think that for low rates this should be done underground? What might the worry be if you are on surface. Can you estimate the potential coincidence rate on surface. Hint, the PDG Online has useful information on this....
4. Would you have substantially different answers to the last two questions if the setup was optimized for looking for U coincidences instead .... can you quantify this?
5. The setup used is pretty basic. If you wanted to make a much more certain measure of the coincidence rates, what would you do?