GRIDS
BiPo Low level radiation Counting

Ken Clark and Tony Noble

May 15, 2026

In this lab, students will construct a circuit using standardly available NIM modules, and measure the rate of “BiPo” events in a variety of samples. The lab is deliberately open-ended. Students must first decide what circuit would work, then build and test it. The only limitations are the analogue and logic units available. Hence, students will be most prepared and likely to be successful if they have read this material in advance, and thought about circuit options.

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:

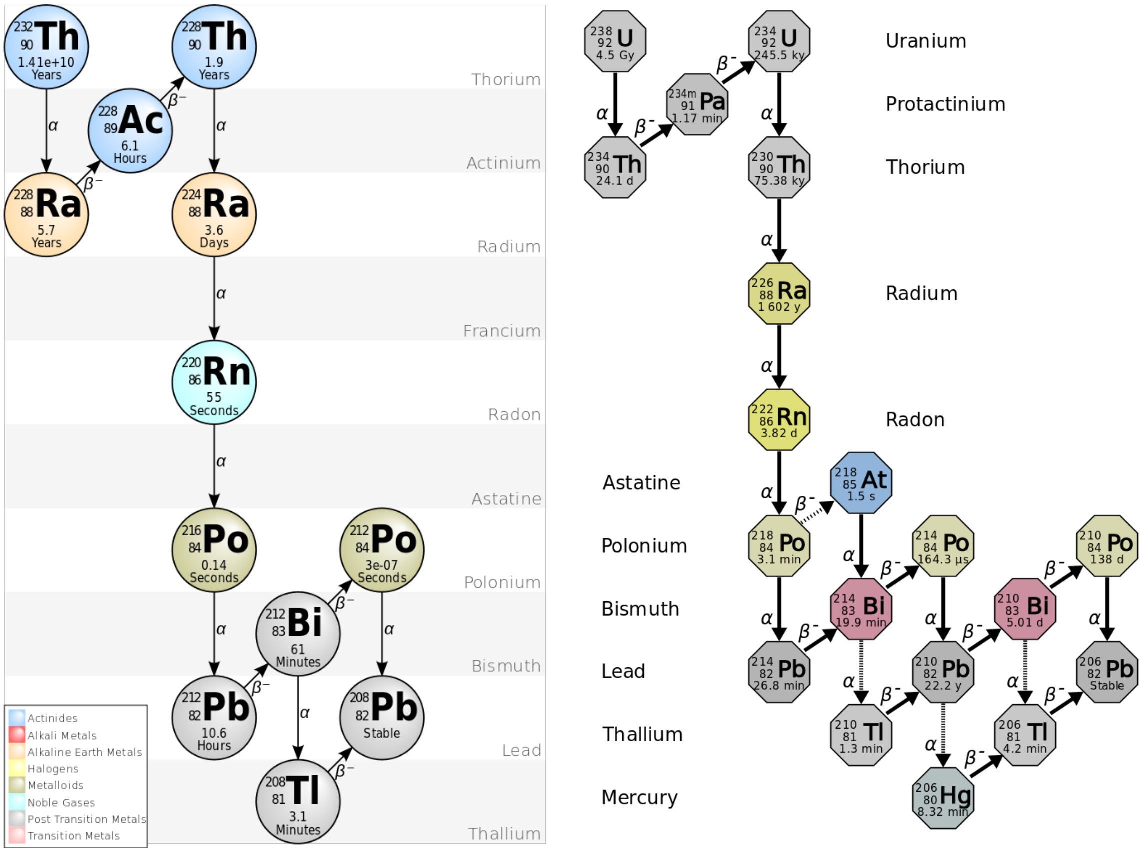
- Reduce backgrounds to ultra-low levels,
- Determine methods to discriminate between signal and any residual backgrounds,
- Find alternate methods of reliably quantifying the amount of background present.

The BiPo method is a very particular tool used to measure the amount of Uranium or Thorium in various samples of interest to the experimentalist. Why these? It turns out that both Th and U (as well as ^{40}K) have life times long comparable to the age of the earth so by now 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}Th and ^{232}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, often in secular equilibrium.
- There are numerous α, and β -decays in each chain, and as well, each of the decays can lead to excited states of daughter nuclei, with the subsequent emission of γ 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. Radon getting into your detector may produce a high radioactivity budget, even if you have worked hard to reduce the amount of U and Th. Astroparticle physicists are not fond of radon.
- 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}Pb near the end of the U chain. Radon decays in the air produce daughters, including ^{210}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:



(a) ^{238}Th Decay Chain

(b) ^{232}U Decay Chain

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

- What is secular equilibrium?
- If the sample is in secular equilibrium how will the decay rate (say in disintigrations per second) 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 β particle, and the decay of the Po produces an α particle. Hence if you could detect a β followed by an α then this would be a good sign that you were seeing events from Th or U. Such coincidences are difficult to see, unless they come in quick succession, otherwise they appear with random time correlation.

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

Likewise in the U chain, for ^{214}Bi → ^{214}Po, the lifetime of the Po is 164 μs. 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 μs. (Keeping in mind of course that these are exponential decays with a mean life τ).

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}Tl, a photon with an energy of 2.6 MeV is emitted, as shown in figure 2.

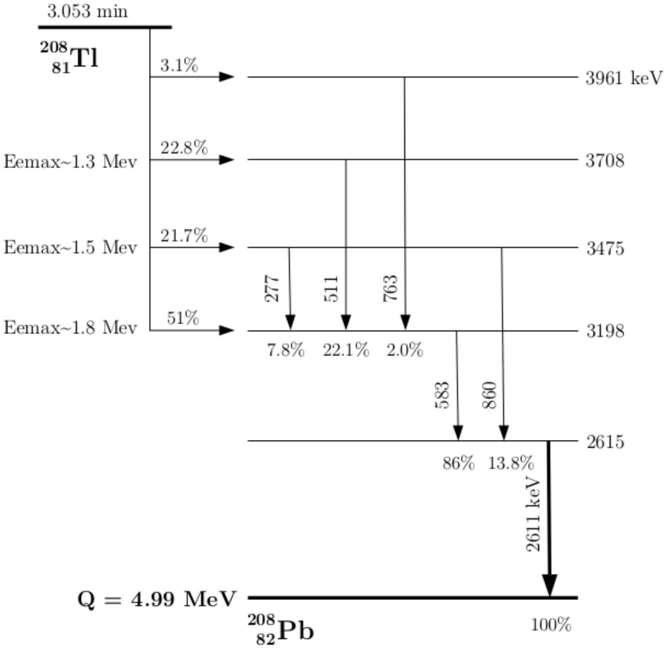


Figure 2: The decay scheme for ^{208}Tl. Note that in 100% of the cases, a photon of energy 2.611 MeV is released. These are a potential problem for SNO if there are any Th or U contaminants (there is a similar problem in the U chain with high energy photons emitted in the decay of ^{214}Bi).

In the SNO experiment we worked incredibly hard to remove all of the U and Th, and their daughters like ^{228}Th and ^{226}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 a column containing 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 material 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 with high efficiency.
- 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 up to about 1 part in 4 of an aqueous solution.
- Then, one simply looks for β α coincidences producing light in the scintillator cocktail.

3 Apparatus

The apparatus is quite simple, but it has not been prepared for you. Your job will be to build the circuit and get it to work using “standard” NIM modules. (“Standard:” Common circuit elements built into fast NIM modules in an era long before you were born).

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!

The students will need to work out the electronics themselves, as it is a good learning experience to set up the logic, and learn how to adjust it. These modules were old when your instructors were using them as graduate students, some decades ago, and they haven’t necessarily improved with age. There may be a number of flaky channels, and it is a bit finicky to get it all to work. If in doubt, get help from the instructor as they have experience in debugging these systems.

So your first job will be to create a logic diagram of the setup, and then you will build it and operate it. Some of the standard modules that should be around include:

High Voltage Power Supply: One unit, with two channels, to be shared by two teams.

Discriminator: Produces an output -800 mV logic signal with definable width when the input analogue signal exceeds a user defined threshold. Sometimes these are also useful for reshaping signals that have become distorted through delays and reflections...

Coincidence Unit: Produces an output signal when two (or more) input signals arrive "at the same time", i.e. when the two input signals each have a logic level "low" overlapping in time. This is a fancy AND gate.

Fan-in/Fan-out: A logic unit which can either make an "OR" of a number of input signals (Fan-in), or which can divide the input signal into a number of identical output channels.

Delay Units: Passive device (really just coiled spools of wire with switches to select the length) that allow you to delay some signals to make signals arrive at the next unit at the times you control.

50 Ω Terminators: Lots of them. Fast NIM electronics uses a standard where the input impedance of the input and output channels is a standard 50 Ω. Hence connecting two modules should preserve the 50 Ω matching impedance, but unused channels will need to have this 50 Ω impedance provided by you where necessary.

Counter: A device to count the number of coincidences, (or any logic signal you wish), to get the count rates. These will likely be "visual scalers" and you will just record the numbers. This is your data.

Amplifier: If the signal is weak, an amplifier may be required, but normally we expect the light output to be enough to easily see the signals without the need for amplification.

DVM: Digital voltmeter, which you will need to measure the threshold settings.

Scope: An oscilloscope to examine the signal shapes and timing as you develop the circuit.

MCA: Multi-channel analyser. May be available. We are working to see. This would allow you to also measure the pulse heights for the α and β particles (proportional to the energy deposition).

4 Instructions/Ideas

As mentioned above, the first step will be to design, build and understand the electronics logic. Remember, the purpose of the electronics is to count the number of coincidences separated in time. Since we will be providing a calibration source (With ThO_2) we suggest that you set up the circuit in a way that you will be counting Th coincidences. We suggest you design/build the circuits, and then test using the Th calibration source. Then find your favourite liquid, and try to see if it has any Thorium activity in it. This may require counting for several hours (in the SNO experiment we counted for several days).

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.

- Before putting the sample on the PMT. Check/double-check that the power of 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. Smear the pot around until the bubbles at the interface are gone.
- 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 α and β 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 you probably used is pretty basic. If you wanted to make a much more certain measure of the coincidence rates, what would you do?