Alpha Energy Loss in Air

PHYS 350 and ENPH 353

October 12, 2017

1 Learning Goals

By the end of this experiment students should be able to:

- Explain basic concepts of radioactivity
- Know basic techniques of counting and spectroscopy experiments
- Calculate mass stopping power of alpha particles in air
- Use the Red Pitaya STEMlab as a function generator, oscilloscope, and multichannel analyzer
- Calibrate a charge and voltage amplifier with operational amplifiers (op-amps)
- Perform curve fitting using Python or MATLAB

2 Safety

Radioactive sources will be used in this experiment. **You MUST have attended the radiation safety lecture and be listed in the department's license to continue.** If you haven't, please see your instructor. To minimize exposure to radiation, make sure to follow these guidelines:

- No food or drink in the lab
- Keep sources at least 10 cm away from your body
- Do not touch the surface of the sources and minimize the time spent carrying sources
- Be careful with the sources to ensure they stay sealed – if an accident occurs, make sure nobody gets in contact with the material and inform your instructor

3 Background and Theory

This lab is intended to function as a first introduction to particle physics. You will use a silicon semiconductor detector, a customizable charge and voltage amplifier, and the Red Pitaya STEMlab device to investigate the alpha decay of an ^{241}Am radioactive source and alpha particle energy loss in air.

3.1 Radiation

Radiation is the emission or transmission of energy in the form of waves or particles through space or through a material medium. In particle or nuclear physics, the most commonly considered types of radiation are alpha particles (α), beta particles (β), and photons including gamma rays (γ) and X-rays. Gamma rays and X-rays are high energy photons, β radiation consists of high energy electrons or positrons (positively charged electrons), and alpha particles are helium nuclei (a compound of two protons and two neutrons).

Radiation is often categorized as either ionizing radiation or non-ionizing radiation depending on the energy of the particles. Ionizing radiation is radiation that carries enough energy to remove electrons from atoms or molecules. In order to remove an electron from an atom, a certain amount of energy must be transferred to the atom. According to the law of conservation of energy, this amount of energy is equal to the decrease of kinetic energy of the particle that causes the ionization. Therefore, ionization becomes possible only when the energy of incident particles (or of the secondary particles that may appear as a result of interactions of incident particles with matter) exceeds a certain threshold value, the so-called ionization energy of the atom. The ionization energy is usually of the order of 10 eV (1 eV $= 1.602\times10^{-19}$ J).

3.2 Radioactive decay

Radioactive decay is the process by which an unstable atomic nucleus loses energy by emitting radiation. A material containing such unstable nuclei is considered radioactive. Radioactive decay is a random process and it is impossible to predict when a particular nucleus will decay regardless of how long the nucleus has existed. However, for a collection of nuclei, the expected decay rate is characterized in terms of its measured half-life, $t_{1/2}$, which is the time required for the number of nuclei to reduce to half its initial number. A radioactive decay can be described by the following formula:

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau} \tag{1}$$

$$N(t) = N_0 \, e^{-\frac{t}{\tau}} \, , \tag{2}$$

where $N(t)$ is the number of nuclei that still remains after time t, N_0 is the initial number of nuclei at $t = 0$, and τ is the mean lifetime of the nucleus with

$$t_{1/2} = \tau \ln(2) \, . \tag{3}$$

We will use ^{241}Am radioactive sources as our alpha emitters. ^{241}Am has a half-life of 432.2 years and it mainly decays through alpha decay. The α-decay energies are 5.486 MeV for 85% of the time. There are lower energy alphas produced in ^{241}Am decays but with much lower intensity. ^{241}Am is an artificially-produced isotope that used in smoke detectors – which is where these sources were obtained. It is important to recognize that the radioactive decay of any particle is a random process - we can't predict when it will happen, and only describe the decay statistically. Thus the number of decays in a given time is given statistically by the Poisson distribution.

3.3 Radiation interaction with matter

The mechanism of interaction of particles with matter depends on the nature of the particles especially their mass and electric charge. In nuclear physics, the term "heavy particles" refer to particles with mass much larger than electron mass, which is equal to 0.511 MeV $= 9.11 \times 10^{-31}$ kg. Alpha particle is an example of a heavy particle with rest mass equal to 3.727 GeV$=6.64 \times 10^{-27}$ kg. The main mechanism of the energy loss of heavy charged particles is ionization or excitation of the atoms in the medium. Excitation is a process that belongs to non-ionizing radiation, in which the internal energy of the atom increases, but it does not lose any electrons.

We will be investigating alpha particles, which are produced by nuclear decays and typically have kinetic energies measured in MeV. As alpha particles travel through matter their two positive charges mean that they interact very strongly, creating lots of secondary excitations and losing energy rapidly. Alpha particles knock electrons out of atoms, then continue on with less energy and eventually come to rest. By conservation of momentum, the largest amount of energy an alpha particle can lose in any one collision is $4E_\alpha m_e/m_\alpha$, or about $1/500$th of E_α. The electrons knocked out of an atom by the alpha particle may have enough energy themselves to continue ionizing the material, so that each alpha particle can create many thousands of mobile electrons in a material. At any given time the particle is interacting with many electrons, so the net effect is a continuous loss of energy until the alpha is stopped [2].

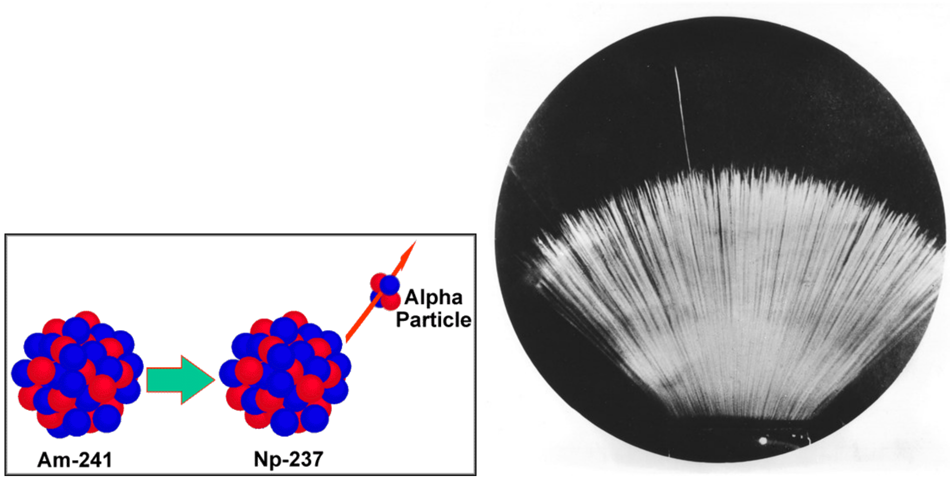

Figure 1: Left: A schematic of alpha-decay of Am-241 producing Np-237 and an alpha particle. Right: Tracks of alpha-particles from Thorium, with one long track of range 95 mm. This photograph, made by the physicist Lise Meitner in the early 20th century [1], shows that alpha tracks are generally a straight line until they stop.

The distance an alpha particle travels in a material including air is known as the range and depends on the rate at which it loses energy in the medium. This rate of energy loss is called the stopping power and is denoted s:

$$s = -\frac{dE}{dx}\,. \tag{4}$$

It has units of MeV/cm. The negative sign brings the stopping power back to positive since energy loss dE is a negative number. A more commonly used term is the mass stopping power $S = -dE/dX$. This is the stopping power divided by the mass density of the material that the particle is traveling through. It is often expressed in MeV cm^2/g. Figure 2 shows the mass stopping power of alpha particles in air with standard temperature and pressure. The mass stopping power reaches a maximum at around 1 MeV then decreases.

The widening of particles' energy distribution as they pass through matter is called energy straggling. As heavy charged particles pass through matter, they lose energy in small amount in each collision over a large number of collisions. It is expected that there will be statistical fluctuations in the energy loss by particles with the same incident energy traveling trough the same distance. These fluctuation effects are known as energy straggling.

3.4 Detection of radiation

To observe the electrons produced from alphas ionizing the atoms in the medium, we must use a detector such as a counter or spectrometer. A counter detects the presence of individual particle events. Measuring the event rate gives information about the activity of radiation − how many particles are emitted per second. A familiar example is a Geiger counter, which uses gas filled detectors and large electric fields to detect the drift of electrons and ions created by collisions with high energy particles. A spectrometer, on the other hand, is a more advanced detector that is concerned with both the number and energy of events.

Spectrometers measure the energy deposited in a medium − often using scintillation (measuring the light produced by ionizing particles), thermal detection (measuring the heat produced) or ionization detectors (measuring the charge produced). One common group of spectrometers are built around semiconductor crystals like silicon. In these detectors, alphas produce a large number of mobile electrons and holes (a "hole" is the absence of an electron in an otherwise full valence band, and can move through a crystal as if it were a positively charged particle) which are swept from the crystal by an

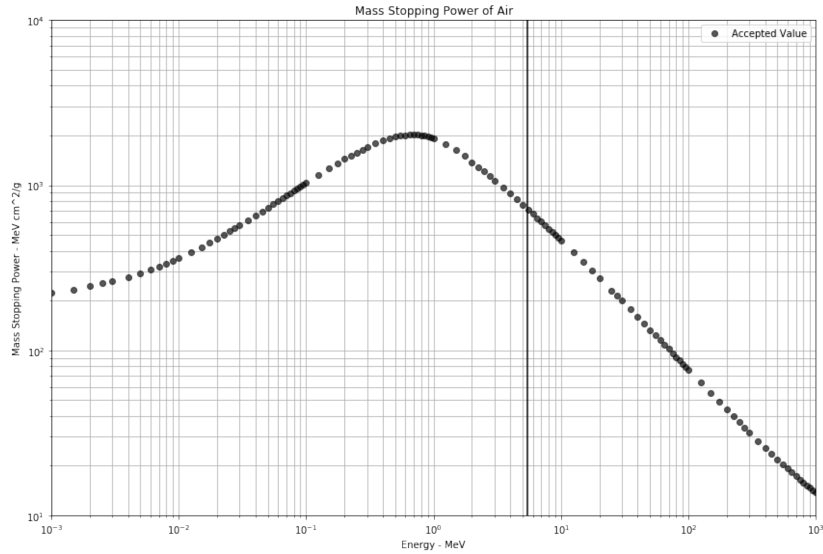

Figure 2: Mass stopping power of alpha particles in air with standard temperature and pressure. Figure is from [3]. The vertical line at 5.486 MeV is the full energy alphas coming from ^{241}Am decay.

electric field. The movement of electrons and holes produces a current pulse proportional to the energy of the alpha interaction that can be amplified and measured. The large alpha energies give rise to measurable amount of charge, and the uncertainty in the value goes as the square root of the count, so the relative uncertainty in the measured energy from a semiconductor detector is relatively low. To detect gamma rays and beta radiation, ionization detectors need to be large because the particles penetrate deeply into matter. On the other hand, alpha particles interact so strongly that even a thin film of material will stop them, and thus the detectors can be much smaller and cheaper.

We will use a silicon PIN photodiode in this experiment as an alpha counter and spectrometer. A PIN photodiode is a diode with a wide region of **intrinsic** semiconductor material (undoped) contained between a **p-type** semiconductor (doped with impurities that have excessive holes) and an **n-type** semiconductor (doped with impurities with excessive electrons). They are typically used to detect light, however we can also use them for radiation detection. When an alpha particle interacts with silicon in the intrinsic region, it creates electron-hole pairs. A diode contains a small built-in electric field due to the n- and p-dopants, but an optional electric field can be applied externally [2]. With an electric field, the electrons and holes move in opposite directions and the charges are collected (see figure 3).

4 Experiment

4.1 Charge and voltage amplifier

The number of charges produced in the PIN photodiode detector is proportional to the energy deposited by incoming particles in the detector. When an alpha particle hits the PIN photodiode detector, it is completely stopped inside the detector and loses all its energy. Therefore, the number of charges produced is proportional to hte initial alpha particle energy. Because alpha particles are completely stopped in the photodiode detector and lose all its energy the alpha particle is proportional to the charge collected in the diode.

A charge amplifier is a current integrator that produces an output voltage proportional to the integrated value of the input current. The voltage produced is still quite small, so we follow this charge amplifier with a voltage amplifier in order to make the signal big enough to be measured using the Red Pitaya STEMlab.

We have built some reconfigurable – yet high performance – amplifier units to be used in this

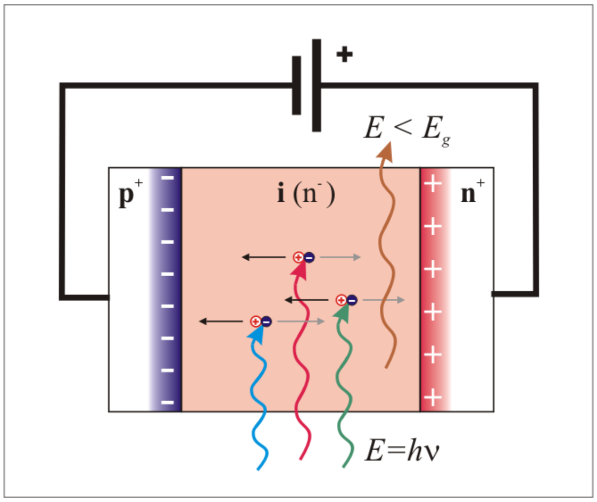

Figure 3: A schematic of a PIN photodiode. Incoming photons or alpha particles ionize the silicon atoms in the intrinsic region and produce electrons and holes. The electric field in the device separates the charges, and the current is proportional to the energy deposited in the photodiode [4].

experiment as well as later in your projects as needed. Operational amplifiers (op-amps) are integrated circuits that operate as nearly-ideal voltage amplifiers, and by using feedback, can be implemented as a host of different circuits. A description of op-amp circuits is available in any electronics book, but we provide the chapter from the "Art of Electronics" by Horowitz and Hill [5] in onQ.

Figure 4 shows the amplifier that is used to collect and amplify the charges produced in the PIN photodiode detector by alpha particles interactions. The central piece of this amplifier is a two-stage op-amp chip (LT1126) mounted onto a printed circuit board. By placing the circuit in this shielded metal box on a circuit board, the performance of the circuit will approach that of a commercial amplifier. However the circuit is fully reconfigurable by changing the location of passive components on the board, similarly to a breadboard. For this experiment we are giving you the circuit, but you will be able to change these later as needed.

The charges produced from the interaction of alphas with the PIN photodiode come in through ‘Amplifier Input’ and are first converted into voltages in the first part of the circuit through a charge amplifier labeled as A. These voltages are then amplified in a voltage amplifier in part B. The power supply for the amplifier is ± 15 V and can be supplied by the breadboard on your desk.

Task 1. Calculate the transfer function (or gain) of the amplifier $G2 = \frac{V_{out}}{Q}$ given the circuit characteristics shown in figure 5, which is dependent on the resistors and capacitors in the circuit. This will also be measured in the next steps.

4.2 Use STEMlab to calibrate the charge amplifier

While we have found the gain of the amplifier in Task 1 above, there are non-idealities in this circuit that can modify this gain. In particular, this charge amplifier relies on a very small capacitor C_F that varies significantly from device to device. The amplification factor needs to be calibrated in order to later convert charge to alpha particle energy. To do this, we will use the Red Pitaya STEMlab device as a function generator and oscilloscope. A Red Pitaya STEMlab is a 14-bit single-board computer that includes analog inputs where the voltage can be measured very frequently $-$ 125 million times per second! This amount of data is too much to be processed in real time on most computers. Therefore Red Pitaya also incorporates a field programmable gate array (FPGA), which is a digital circuit that can be reconfigured as needed using software.

Task 2. To calibrate the amplifier we will send a known amount of charge into the amplifier and measure the output voltage. We can do this by sending a current pulse with a given duration. We will use the STEMlab’s output to send a short pulse of voltage, and convert that to a current by

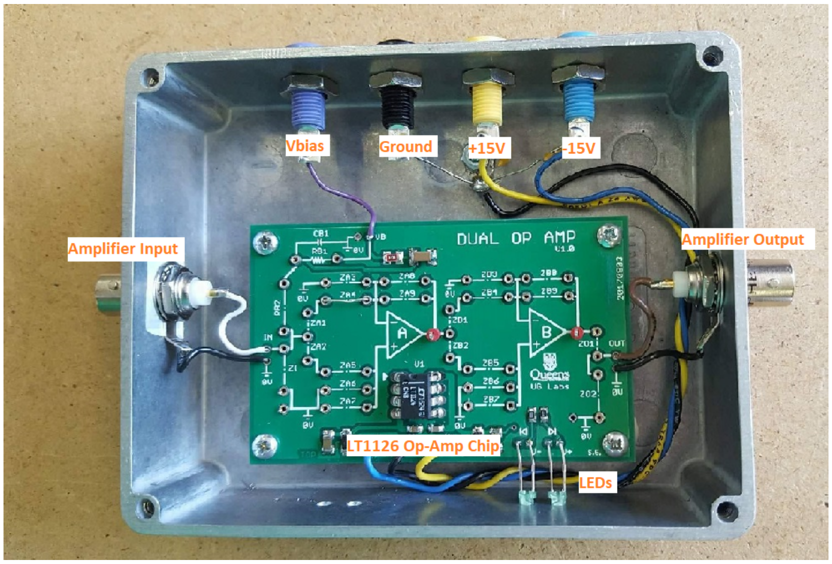

Figure 4: Reconfigurable charge and voltage amplifier board. Note that this board has not been populated with resistors, capacitors, or jumper wires.

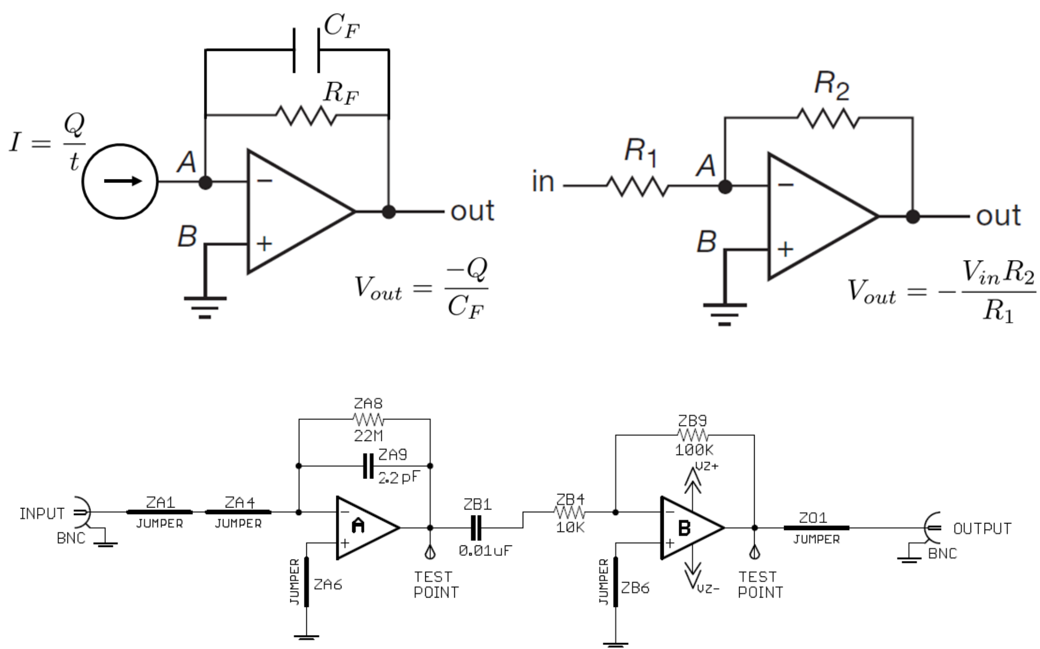

Figure 5: Top Left: The simplified schematic of a charge amplifier, which has output $V_{out} = \frac{Q}{C_F}$. Top Right: Simplified schematic of an inverting voltage amplifier, which has voltage gain $G3 = \frac{R_2}{R_1}$. Bottom: Circuit diagram for the two-stage amplifier circuit diagram as built. The nominal gain of the circuit is $G_2 = \frac{V_{out}}{Q} = \frac{R_2}{R_1 C_F}$.

putting a resistor in the input. As shown in figure 6, open the amplifier and replace jumper ZA4 with a 10 MΩ resistor. **Always make sure to turn off the circuit power supply before doing any modification.**

Connect the amplifier in a calibration circuit following the connections shown in table 1. When the amplifier is properly powered with ±15 V, the two LEDs on the side of the box should light up.

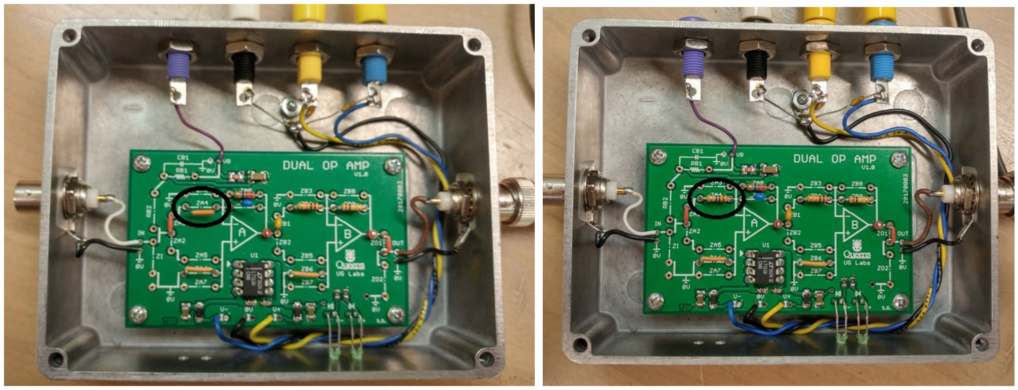

Figure 6: In task 2 of the experiment, replace the jumper at ZA4 on the circuit board (left) with a 10 MΩ resistor (right). The key circuit element is circled in black in both figures.

To troubleshoot unlit LEDs, first check the power cable connections to the breadboard, then check the fuse on the breadboard that corresponds to the unlit LED power line. The lid of the amplifier box should be closed to reduce any pickup of signals from the environment. Do not overtightened the screws.

Amplifier	**Connection**
Vbias	No connection
Ground	Ground on breadboard
+15 V	+15 V on breadboard
−15 V	−15 V on breadboard
Amplifier Output	STEMlab IN1
Amplifier Input	STEMlab OUT1

Table 1: Connections between the amplifier, breadboard, and STEMlab for calibrating the amplifier.

Task 3. You will generate voltage pulses from the STEMlab and measure the amplified signal. To connect to the STEMlab, open the following web page on the desktop or your laptop: `http://labs.phy.queensu.ca/rpXX` where XX is the number taped on top of the STEMlab. Double check this number to make sure you are not controlling someone else's device. Start the Oscilloscope and Signal Generator app. To generate voltage pulses on STEMlab OUT1, put the OUT1 settings on the web page as

- Type=PWM
- Frequency=10000 Hz
- Duty Cycle=1.5%
- Amplitude=0.5 V

The above settings should generate a square pulse with 1 V peak-to-peak amplitude with 1.5 μs in width. This voltage pulse goes through a 10 MΩ resistor, so the current is $I = V/R = 1\text{V}_{pp}/10^7\Omega = 10^{-7}$ A. The goal of the amplifier is to integrate the current and give a peak output voltage proportional to the charge. STEMlab IN1 shows the signal coming off the amplifier output, which should look like a series of pulses which decay slowly as the amplifier resets. The amplitudes of these pulses can be measured using the CURSOR menu in the oscilloscope. Move the Y-axis cursors one to the baseline of the pulse and the other to the maximum of the peak to find the amplitude. Find the gain G_2 of your charge amplifier in units of V/C. This gain can be compared to the nominal gain G_2 taken from the circuit components $G_2 = \frac{R_2}{R_1 C_F}$. Compare these and comment.

Task 4. There is another calibration we need in order to properly find the energy of alpha particles: this is the amount of charge detected in the photodiode per energy of the incoming alpha particle. We have done this calibration for you by putting the apparatus in vacuum so that there is no energy attenuation in air. We find that this calibration factor is $G_1 = 0.264 \pm 0.001$ electrons/eV = 0.264 ± 0.001 C/J. Thus, when we connect the photodiode to the amplifier and read the output with the STEMlab, we have a complete calibration:

$$V_{pp} = G \times E_\alpha = G_1 \times G_2 \times E_\alpha \,. \tag{5}$$

This gives the expected voltage coming out of the amplifier for an alpha particle with an energy of E_α. The nominal energy of alpha particles released from ^{241}Am is 5.486 MeV. Calculate the expected measure V_{pp} for a full energy alpha particle.

4.3 Detecting alpha particles

The most common house-hold smoke alarm is an air-filled ionization chamber. There is a small amount (~ 0.8 μCi) of ^{241}Am radioactive source in the detector giving off alpha particles. They ionize oxygen and nitrogen in the air inside the chamber and create electron-ion pairs. The electrons are attracted onto the positively charged plate and the ions are collected onto the negatively charged plate, therefore producing an electric current. When there is smoke in the house, the smoke gets in the detector and interferes with this ionization, reducing the current. The smoke detector senses the drop in current between the plates and sets off the alarm.

With permission from the Queen's Safety Department we are using these ^{241}Am radioactive sources from the smoke detectors as our alpha particle emitters. The sources are mounted onto a red Lego block. **Be careful handling this Lego block. Do not touch the surface of the alpha source. Do not drop this Lego block.** The detector we use is a silicon PIN photodiode from Hamamatsu (S1223-01) with a sensitive surface area of 3.6×3.6 mm^2. The PIN photodiode is mounted onto an electrical box for grounding purpose as well as keeping it in dark to reduce photon background events. There is a Lego block glued on the bottom of this electrical box. While there is no danger to you, the photodiode has had its protective glass removed, and thus can be easily damaged. **Do not touch the photodiode front surface.**

Task 5. Build a structure to support the red Lego block so that the ^{241}Am source faces towards and is centered with the PIN photodiode detector. Be careful not to touch either the source surface or the PIN photodiode detector surface. This structure will also allow you to move the radioactive source closer or farther away from the detector by adding more Lego blocks in between or move the structure in steps on the bottom Lego block. Your structure should allow moving the alpha source in small ($\leq$2 mm) steps.

Task 6. Replace the 10 MΩ resistor at ZA4 in the amplifier back to its original settings with a wire jumper. Be sure to turn off the $\pm$15 V power supply before doing this. With the ^{241}Am source around 1-2 cm away from the detector, close the electrical box lid and tighten with screws (do not overtighten the screws). The charge coming out of the photodiode (labelled as "Photodiode Output" on the detector box) goes to "Amplifier Input" on the amplifier. The charge signal is converted into voltage and amplified. The "Amplifier Output" should be connected to "STEMlab IN1" as an input to the STEMlab device.

Task 7. You should see alpha pulses on the STEMlab oscilloscope. Note that the amplitude of each pulse is proportional to the energy deposited in the silicon PIN photodiode detector by alphas, which in this case is the full energy of alphas since they are completed stopped inside the detector. Background radiation for example gamma rays deposit some energy in the photodiodes as well but these background event rate is much smaller than alphas coming out of the ^{241}Am source. What is the typical alpha pulse amplitude measured from the baseline of the pulse to the peak? Estimate the risetime which is the time taken on the rising edge for the amplitude of the pulse to go from 10% of to 90% of its peak height. Also estimate the decay time, which is the time required for the amplitude of the pulse to decrease to approximately 37% (or $1/e$) of its maximum peak height. The risetime is dependent on how fast the electrons and holes move in the photodiode before they are collected in the amplifier and it should be on the order of 1 μs. The decay time is a feature of the amplifier decay constant and it should be on the order of 100 μs.

Task 8. We will now take an energy spectrum for the alpha particles manually. Have the oscilloscope on single trigger mode and use the CURSOR function to measure the amplitudes for $\sim$10 pulses. Don't worry if there are several peaks on top of each other – this is called "pile-up" and these data points will be obvious when we take more data. Histogram these 10 pulse peak heights in your lab notebook (counts versus peak heights). You have now successfully plotted an alpha energy histogram. Note that the X-axis is in voltage, but you can use the calibration determined above ($G_1 * G_2$ to convert this to energy.

You will notice that 10 data points are not nearly enough to give any reasonable sense of the spectrum. When counting the number of peaks in a given bin, Poisson statistics apply – this means that the uncertainty in that count is given by the square root of the number of counts N. In order to measure the spectrum well, we need to have enough data so that $\sqrt{N}/N$ is small.

4.4 Multichannel analyser

The multichannel analyser (MCA) is essentially a tool for measuring and histogramming the particle pulse heights, similar to task 8 but in a more sophisticated way. The MCA app on the Red Pitaya STEMlab is one example of novel application developed by incorporating custom FPGA code [6]. The MCA will be used to capture a histogram of counts versus pulse peak heights which is proportional to the alpha energy in the PIN photodiode detector. Figure 7 shows the home screen of the MCA app in the background and the pulse illustration is shown at the front.

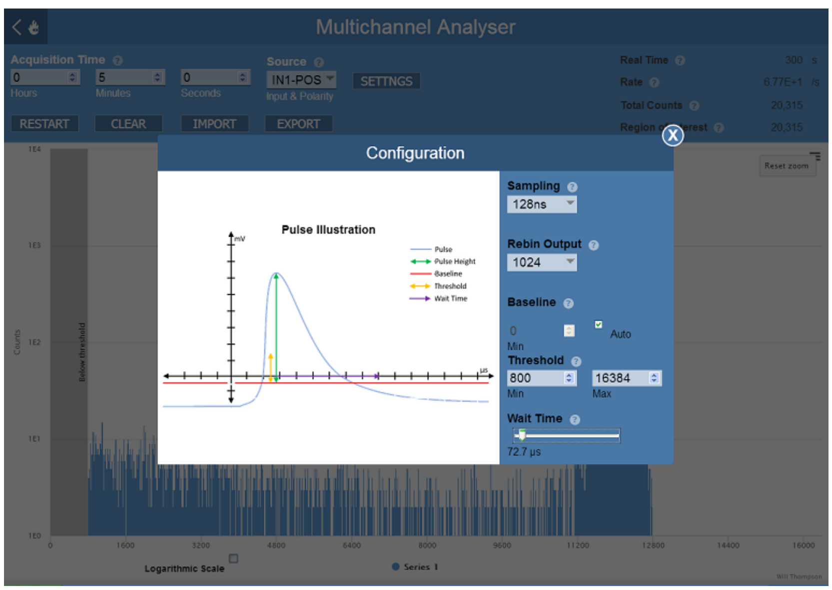

Figure 7: Multichannel analyser home screen is shown in the background of this figure and the configuration of baseline, pulse height, etc. is shown at the forefront.

The settings for measuring the pulse height of this raw pulse include:

- Sampling: the averaging window before the pulse is analysed. Note that the minimum sampling window is the inverse of the sampling rate which is 1/(125 MS/s) = 8 ns. Use the default value as 128 ns.

- Rebin Output: the number of bins on the X-axis. The X-axis is what we call the channel number. Since we are using STEMlab IN1 with a maximum peak-to-peak range of 2 V, the default value of 1024 bins gives 2 V/1024 = 1.953 mV/channel. Note that when you export the histogram into a CSV file later, the number of bins on the X-axis is always 2^{14} = 16384, independent of this Rebin Output setting. With a 2 V maximum range and 16384 bins, it gives 2 V/16384 = 0.122 mV/channel. Use the default value of 1024 bins.

- Baseline: the base of the pulse for measurement. Auto baseline means it will measure the pulse height from the most recent minimum of the signal. Sometimes the baseline of the signals may shift due to electronics noise or other effects. Auto Baseline will allow to shift the baseline to automatically correct for this.
- Threshold: the minimum and maximum amplitudes of a pulse from the baseline. Only pulses with amplitudes within this range will be counted. You should set a minimum that is larger than the amplitude of the noise. Try taking data with a minimum threshold at 0 first. You will see both the noise peak on the left and the signal peak on the right (higher energy events). Now set the minimum threshold at the edge of the noise peak, typically at a few hundred channels for our system.
- Wait Time: the time to wait after a pulse reaches its maximum before searching for the next pulse. This parameter is important if the alpha source is close to the detector. In this case, a lot of alpha particles arrive at the detector close in time. The amplifier sees another alpha signal before the previous one ends. Therefore the pulses overlap in time and they are the so-called pile-up events. You will need to set the wait time to be longer than the width of the pulse (typically around 80 μs) to get rid of the pile-up events. Note that the non-zero wait time reduces the pulse collection rate.

The settings on the MCA home screen include the following:

- Acquisition Time: the time the MCA will take data for.
- Source: this shows the Red Pitaya port you are taking data with and the polarity of the pulses.
- Real Time: the amount of time passed since the acquisition started. To calculate livetime, subtract the wait time you selected multiplied by the total number of event counts.
- Rate: the average number of events per second.
- Total Counts: the total number of events registered.
- Region of Interest: the number of events in the zoomed-in region.
- "START" toggles with "RESTART" and "STOP" and it starts, restarts, or stops data taking.
- Use "CLEAR" to reset the histogram.
- "IMPORT" and "EXPORT" allow to import or export data files in CSV format.

The shadow on the left side of the histogram shows up when you set the minimum threshold to above zero. You can zoom in or out on the X-axis or toggle between normal and logarithmic scale on the Y-axis. The icon on the left top corner of the histogram allows you to print the histogram into files of different formats.

Task 9. With the radioactive source mounted as close as you can safely do using the Lego blocks, take an energy spectrum of the ^{241}Am alpha particles. With default MCA settings you should see two peaks. The peak around 0 is the noise peak caused by electronics noise and low-energy background events. You should set the MCA threshold close to the right edge of this noise peak which should be between 300-600 MCA channels. There should now only be one peak left which are events from alpha particles. The "Total Counts" on the MCA tells us how many particles were detected in a given time. If the activity of the source is 0.8 μCurie, how many detections would you have expected? Why is your number different?

Task 10. With the source mounted from close to far (up to 5 cm away until you do not see any alpha peaks any more), measure the energy histograms at each position. Use Lego blocks as discrete steps in distance. Take energy histograms using the MCA app and export all data into CSV files.

Keep in mind the more counts you have in each bin, the smaller the statistical uncertainty will be. Therefore, to reduce the uncertainty you should aim to have a smooth peak to allow for a better fit in the next task. For each energy histogram, you should write down all MCA settings you recorded data with (including the "Real Time"), the output filename, and the distance between the alpha source and the PIN photodiode detector. Remember to close the lids on both detector and amplifier boxes to reduce background events. As you move the source farther away from the detector, the energy peaks moves towards the left side because alphas arrive at the detector with a lower energy. When the peak energy is below your threshold (in other words overlapping with your noise peak), you have moved the source too far and you will not be able to separate the alpha energy peak from the noise peak. Note that the bumps on Lego bricks are placed every 8 mm, and a standard brick is 9.6 mm tall, while a plate is 3.2 mm thick.

Task 11. Find the peak value of the alpha energy peak for each distance. Now we would like to go through and fit a function to each alpha energy peak. In most cases a Gaussian function is appropriate for fitting:

$$Y = Ae^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{6}$$

This is sufficient for our purposes. Note that σ is often defined as the detector energy resolution. The larger width of the alpha energy peak means that the spread (uncertainty) of pulse heights is larger, which corresponds to poorer energy resolution. Convert these numbers from MCA channel number to energy in MeV, knowing that 16384 channels correspond to 2 V (with ± 1 V in range) and the measured conversion of voltage to particle energy is $G = G_1 \times G_2$. Since the vertical axis is number of counts, the uncertainty in the count in each bin is its square root. You should take this uncertainty into account when you do the fit. The uncertainty in the centroid μ of a Gaussian peak with N counts in the peak is given by

$$\sigma_\mu = \frac{\sigma}{\sqrt{N}} \,. \tag{7}$$

If you want a challenge, a modified Gaussian (equation 8) that has a different standard deviation on either side of the peak accounts well for its asymmetry due to smaller mass stopping power at higher alpha energy (figure 2). We will also leave the long tail from straggling out from the fit.

$$Y_{\text{modified}}(x) = A\, e^{\frac{-(x-\mu)^2}{2\sigma_{l,r}^2}} \,, \tag{8}$$

where μ is the peak position and $\sigma_{l,r}$ are the standard deviation on the left and right side of the peak, respectively. See below for an example python code for defining the modified Gaussian in Equation 8. This modified Gaussian gives a better fit to the alpha energy spectrum than a normal Gaussian function.

```
def modified_gaussian_scalar(x, *parameters):
    A, mu, sigma_left, sigma_right = parameters
    if x < mu:
        return A*numpy.exp(-(x-mu)**2/(2.*sigma_left**2))
    else:
        return A*numpy.exp(-(x-mu)**2/(2.*sigma_right**2))
```

4.5 Alpha energy loss in air

The following exercises will allow you to calculate alpha energy loss in air.

Task 12. First let's calculate the mass density of air in Kingston using an online tool at https://www.brisbanehotairballooning.com.au/calculate-air-density/ and weather data from https://weather.gc.ca/city/pages/on-69_metric_e.html for the day you did this experiment. Note that 1 kPa = 10 hPa. You should also convert the air density from kg/m^3 to g/cm^3.

Task 13. Plot the peak energy as a function of distance from the source to the detector. If you extrapolate towards zero separation, do you get the known full energy of the alpha particles? Explain your findings.

Task 14. Now calculate the mass stopping power of air $-dE/dX$ at each distance you took data with (except the farthest point). You must calculate an approximation to the derivative of the energy with separation, and convert this separation to the amount of mass the particles traversed. You have $S = -dE/dX = (E_2 - E_1)/(X1 - X2)$ as you move the source from position 1 to position 2. $X = x * \rho$ where x is the distance you measured from source to photodiode and ρ is the air density from task 12. Compare your data points with literature data from [3] (see Appendix A).

Task 15 (optional). Extrapolate the range of alpha particles coming off the ^{241}Am source in air. The expected value at standard temperature and pressure is 4.1 cm for 5.5 MeV alphas [3]. The range is defined as the thickness of material (air in our case) where the alpha particle count is half of its value in the absence of the material. This calculation isn't easy for this experimental system. You will need to take into account the solid angle effect since we expect fewer alpha particles to be detected simply due to geometry as we move the sample away. In many experiments the range is measured instead by pumping the air out from in between the source and detector, while keeping the geometry fixed.

References

[1] Meitner, L., as reproduced in "Contexts for photography collections at the National Media Museum" by Michael Terway, http://dx.doi.org/10.15180/170710

[2] Knoll, G.., "Radiation Detection and Measurement", 4th Edition, Wiley (2010).

[3] NIST stopping power and range table for alphas, https://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html

[4] PhysicsOpenLab, http://physicsopenlab.org/2016/03/08/pin-diode-radiation-detector/

[5] Horowitz, P. and Hill, W., "The Art of Electronics", 3rd Edition, Cambridge University Press (2015).

[6] Red Pitaya MCA application, https://github.com/sefffal/redpitaya-multichannelanalyser

A Mass stopping power literature data

Mass stopping power data for alpha particles in air from National Institute of Standards and Technology is shown below:

```
#Energy (MeV) Mass stopping power (MeV cm^2/g)
data = np.fromstring("""\
1.00E-03 2.22E+02
1.50E-03 2.34E+02
2.00E-03 2.44E+02
2.50E-03 2.54E+02
3.00E-03 2.62E+02
4.00E-03 2.78E+02
5.00E-03 2.94E+02
6.00E-03 3.08E+02
7.00E-03 3.23E+02
8.00E-03 3.36E+02
9.00E-03 3.50E+02
1.00E-02 3.63E+02
1.25E-02 3.93E+02
1.50E-02 4.23E+02
1.75E-02 4.50E+02
```

2.00E-02	4.77E+02
2.25E-02	5.02E+02
2.50E-02	5.26E+02
2.75E-02	5.49E+02
3.00E-02	5.72E+02
3.50E-02	6.15E+02
4.00E-02	6.56E+02
4.50E-02	6.94E+02
5.00E-02	7.31E+02
5.50E-02	7.66E+02
6.00E-02	8.00E+02
6.50E-02	8.32E+02
7.00E-02	8.64E+02
7.50E-02	8.94E+02
8.00E-02	9.23E+02
8.50E-02	9.51E+02
9.00E-02	9.79E+02
9.50E-02	1.01E+03
1.00E-01	1.03E+03
1.25E-01	1.15E+03
1.50E-01	1.26E+03
1.75E-01	1.35E+03
2.00E-01	1.44E+03
2.25E-01	1.51E+03
2.50E-01	1.58E+03
2.75E-01	1.64E+03
3.00E-01	1.70E+03
3.50E-01	1.79E+03
4.00E-01	1.87E+03
4.50E-01	1.92E+03
5.00E-01	1.96E+03
5.50E-01	1.99E+03
6.00E-01	2.01E+03
6.50E-01	2.02E+03
7.00E-01	2.02E+03
7.50E-01	2.02E+03
8.00E-01	2.01E+03
8.50E-01	1.99E+03
9.00E-01	1.97E+03
9.50E-01	1.95E+03
1.00E+00	1.92E+03
1.25E+00	1.78E+03
1.50E+00	1.63E+03
1.75E+00	1.50E+03
2.00E+00	1.38E+03
2.25E+00	1.29E+03
2.50E+00	1.21E+03
2.75E+00	1.13E+03
3.00E+00	1.07E+03
3.50E+00	9.69E+02
4.00E+00	8.87E+02
4.50E+00	8.19E+02
5.00E+00	7.61E+02
5.50E+00	7.12E+02

```
6.00E+00 6.70E+02
6.50E+00 6.33E+02
7.00E+00 6.01E+02
7.50E+00 5.72E+02
8.00E+00 5.46E+02
8.50E+00 5.22E+02
9.00E+00 5.01E+02
9.50E+00 4.82E+02
1.00E+01 4.64E+02
1.25E+01 3.93E+02
1.50E+01 3.43E+02
1.75E+01 3.05E+02
2.00E+01 2.75E+02
2.50E+01 2.31E+02
2.75E+01 2.14E+02
3.00E+01 2.00E+02
3.50E+01 1.77E+02
4.00E+01 1.59E+02
4.50E+01 1.45E+02
5.00E+01 1.33E+02
5.50E+01 1.23E+02
6.00E+01 1.15E+02
6.50E+01 1.08E+02
7.00E+01 1.02E+02
7.50E+01 9.61E+01
8.00E+01 9.12E+01
8.50E+01 8.69E+01
9.00E+01 8.30E+01
9.50E+01 7.94E+01
1.00E+02 7.62E+01
1.25E+02 6.36E+01
1.50E+02 5.50E+01
1.75E+02 4.86E+01
2.00E+02 4.37E+01
2.25E+02 3.98E+01
2.50E+02 3.67E+01
2.75E+02 3.41E+01
3.00E+02 3.19E+01
3.50E+02 2.83E+01
4.00E+02 2.56E+01
4.50E+02 2.35E+01
5.00E+02 2.18E+01
5.50E+02 2.04E+01
6.00E+02 1.92E+01
6.50E+02 1.82E+01
7.00E+02 1.73E+01
7.50E+02 1.65E+01
8.00E+02 1.58E+01
8.50E+02 1.52E+01
9.00E+02 1.47E+01
9.50E+02 1.42E+01
1.00E+03 1.38E+01
""", sep="\t")
tabulated_energies = data[::2]
```

```
tabulated_stopping_powers = data[1::2]
```