BFY III Workshop 20: Alpha Particle Spectroscopy and Energy Loss

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Abstract

Nuclear and particle physics experiments for undergraduates tend to be expensive, such that most universities only have one set of apparatus for each experiment. We have designed an experiment that covers the same learning outcomes as our expensive existing experiments: particle counting, spectroscopy and energy loss, but using reconfigurable and cheap equipment. In this workshop we describe the apparatus, demonstrate the procedure and show the data analysis. The tools in this experiment have been designed to be reconfigurable and used in open-ended projects later in the course, and we discuss this.

Motivation and Courses:

Many advanced laboratory courses involve a sequence of unique experiments, where students rotate through a series of experiments. At Queen's University, we are aiming to have students do significant open-ended experimental projects, so we want preparatory experiments that we can deploy to all students at once, giving the support needed to allow the project to be both ambitious and successful. We have designed an experiment that we ran for 40 students at a time in fall 2017 which addresses the following learning outcomes:

- Learn the basics of radioactivity and work safely with radioactive sources;
- Understand and perform particle counting and spectroscopy experiments;

With secondary learning outcomes:

- Continue to use software for non-linear curve fitting
- Understand calibration of instruments
- Use and modify simple op-amp amplifiers in experiments
- Compare a model to data

Background:

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 and through mylar films. The full instructions for the Fall 2017 lab are available(Knobel et al., 2017).

Theory and Model:

Ionizing radiation produced from radioactive decay takes the form of photons (x-rays and gamma rays), electrons (beta particles), positrons, fission fragments and alpha particles. Alpha particles (α), the ionized nuclei of a helium atom, are both heavy and highly charged, so they interact strongly with matter, ionizing the atoms of the material they pass through. Thus alpha particles lose energy quickly, and the ˜ MeV particles emitted from typical radioactive sources can be stopped by a sheet of paper or a few centimetres of air. This energy loss can be described by the **stopping power** $S\left(E\right) = -\frac{dE}{dx}$, where E is the energy and x the distance traversed in a medium. Often the mass stopping power is used, where the mass stopping power is divided by the material density. Bethe derived a classical relativistic formula describing the stopping power(Knoll, 2010):

$S = \frac{4\pi e^4 z^2}{m_e v^2} NB,$

$B \ = Z\left[\ln\frac{2m_e v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$

where c is the speed of light, v the speed of the particle, z the charge of the alpha particle (ie. 2), Z the atomic number of the absorber atoms, and N the atomic density in the target material. The mean ionization potential of the absorber atoms I is typically taken from tables, though it is approximately $I \approx \left(10\,\mathrm{eV}\right) Z$, allowing a quicker approximation. For non-relativistic particles, only the first two terms in B are important. Since the energy loss of the alpha particles is approximately $S \propto 1/v^2$, so that as the particle slows down, the energy loss increases, meaning that near the end of the particle's track S increases to a peak before dropping as the particle bonds with electrons - the so-called Bragg peak. More precise models of stopping power include the quantum nature of the stopping material and higher order terms, and these are tabulated through the ASTAR webpage at (NIST).

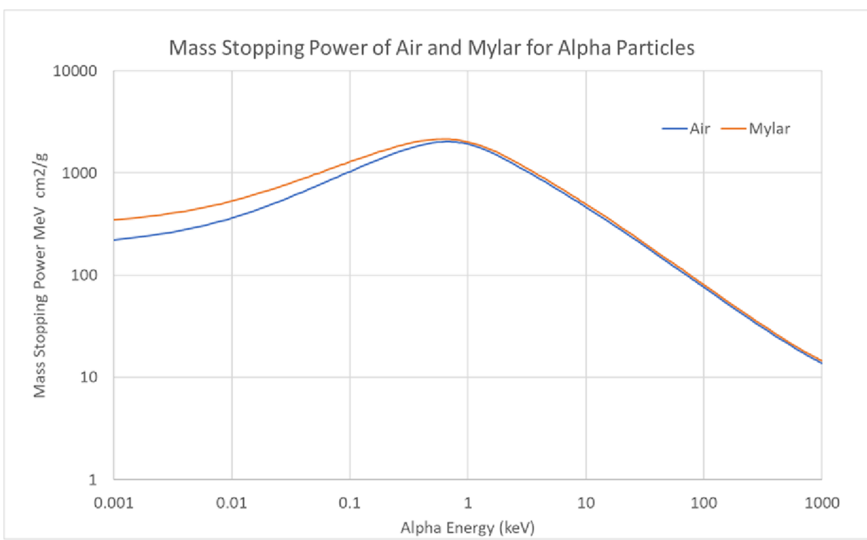

Figure 1: Mass stopping power for alpha particles in mylar (polyethylene terephthalate) and air at atmospheric pressure. For mylar the density is 1.4 g/cm^3 and mean ionization energy $I = 78.7eV$, while for air the density is 1.20479 10^{-3} g/cm^3 and $I = 85.7eV$.(**?**) The table of data is associated with this plot on the Authorea version of the document.

Energy loss of the alpha particles is a stochastic process, so a spread in energies is always expected after a monoenergetic beam passes through a medium. This so-called straggling also causes a skew in the energy distribution, giving a noticeable low-energy tail to the peak.

Apparatus:

The apparatus is designed to be cheap, relatively high-performance, and flexible. We are sharing designs and code for reuse.

Source:

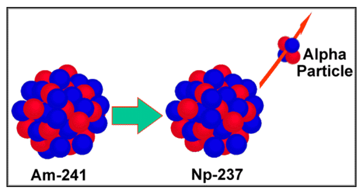

Figure 2: Alpha particle decay in Americium-241

Commercially available ionization smoke detectors (< $10) contain a small ^{241}Am source. We carefully removed the metal cover and mounted them in a 2x4 lego brick. These sources have been added to our approved source inventory and we treat them with the same care and training that we treat expensive thin-film sources. For the BFY demonstration, we are borrowing sources from NYU - thanks to Lorcan Folan! **Do not touch the radioactive source -** these alpha sources have little protective coating. These sources are not as thin as those intended for research purposes, so that some alpha particles emitted from deep within the source have lost energy leading to a broader energy spectrum than is ideal. ^{241}Am emits alpha particles with 5.486 MeV (85% of the time), though measuring the spectrum from these smoke detector sources gives a lower energy. In most cases, experiments to measure energy loss of alpha particles are done in vacuum, or at least in a variable pressure environment. In order to have the experiment done easily by a full class of students, these measurements were done in air.

Detector:

Radiation can be detected in a number of ways: scintillation, gas ionization or in semiconductor charge detectors(**?**). Since alpha particles interact so strongly with matter, they penetrate only a few microns at most, so typically surface barrier detectors such as those from Ortec (Ortec), which collect the charge liberated when a high energy alpha particles excited electrons and holes in a semiconductor. The liberated charge is proportional to the particle energy, so measuring this charge is a measure of alpha energy. These detectors are efficient, have low noise, large area and can measure low background regimes. For simpler measurements such as in an undergraduate experiment or for hobbyists (ope) , a **PIN photodiode** can work as a detector. A PIN has an intrinsic semiconductor region sandwiched between heavily doped P- and N-doped regions - the large intrinsic region lowering the capacitance and decreasing the response time for optical communications. As the alpha particle enters the intrinsic region of the diode it creates electrons and holes, each swept in opposite directions by the built-in-field, creating a measurable charge. After trying several different devices, we found that the Hamamatsu S1223-01 PIN photodiode (Hammamatsu) works well as an alpha particle detector due to its ˜10 mm^2 area and low capacitance, however it doesn't seem to improve its performance with reverse biasing (unlike many such diodes). This diode has a glass window that needs to be carefully removed so that the bare silicon is exposed, and the detector must be kept in the dark. Each diode is approximately $10.

Preamplifier:

We need to amplify the small pulse of current to create a voltage pulse. Commercial charge preamplifiers are available with very high performance and low noise (Cremat), however again we value price, flexibility and pedagogy over performance. We designed a simple printed circuit board with a socket for a dual op-amp that can be reconfigured for different sorts of amplifiers (voltage, current, etc.). Here we use a charge preamplifier followed by a voltage amplifier with a gain such that the full-energy peak for the alphas give a 1 V pulse. These can be reconfigured for use in projects later. We look at this as a reconfigurable amplifier - like that on a protoboard - however with performance approaching that of a commercial system. The PCB, box, connectors and other components total less than $80 each. Designs for our boards are available (Gillen, 2017). We view this amplifier as partway between an exposed protoboard (with uncontrolled pickup, capacitances and poor connections) and an amplifier designed for a single purpose.

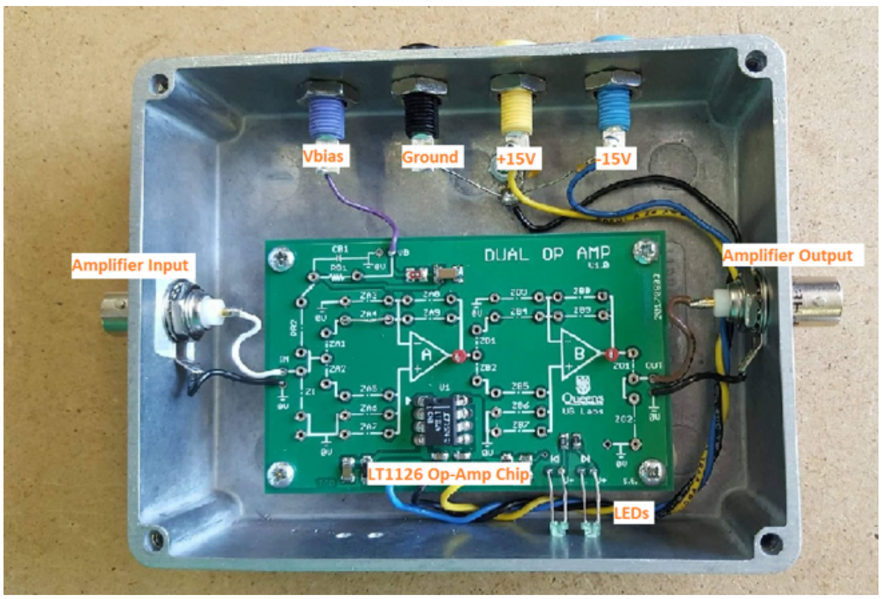

Figure 3: A custom dual op-amp circuit board.

Multichannel Analyzer:

As we mentioned above, the charge produced in the diode is proportional to the energy of the alpha. After the amplifier, this is converted into a voltage pulse whose amplitude is related to the original particle energy. A multi-channel analyzer (MCA) is typically used to measure these pulses, recording the pulse height for each pulse and building histograms for counting. Again, we have designed a flexible instrument that is cheap and can be applied to other purposes. We have purchased several **STEMlab instruments** (Red$_P$*itaya*). These are single-board Linux-based instruments that include a re-programmable FPGA and 14-bit analog outputs and inputs sampled at 125 MS/second. The STEMlab is open source, about $500 (depending on options), can be controlled remotely through Python, LabVIEW and other languages, but also has built-in applications including an oscilloscope, function generator, logic analyzer and others. The FPGA can be reprogrammed, and several interesting applications have been built, including a MCA with source code

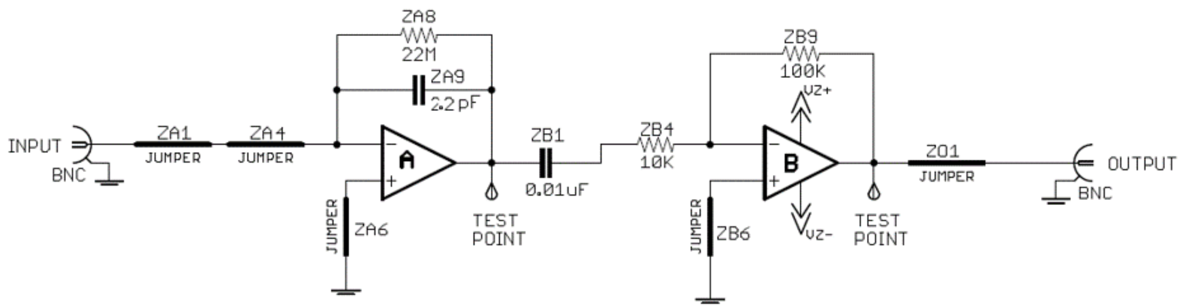

Figure 4: Preamplifier schematic.

available (Demin). We created a web application for this back-end, allowing any web browser to access and control the MCA - with source code and documentation available here (Thompson).

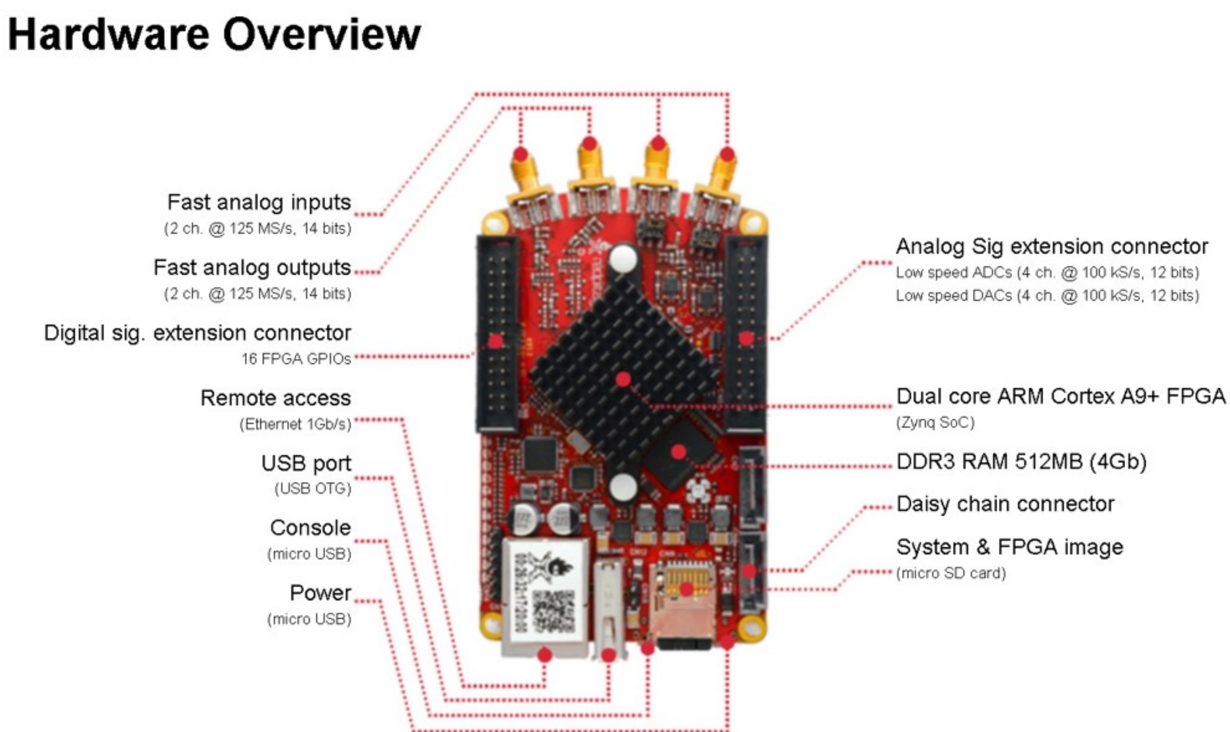

Figure 5: The STEMlab computer from Red Pitaya.

Procedure:

In order to controllably place the radioactive source with respect to the detector we placed a Lego baseplate in the light-tight box containing the detector and source. This allows the students to be able to place the source with reproducible precision, and to have discrete steps to move the sample away without having to use a micrometer.

The energy of the alpha particle is related to the current pulse, and thus the amplified voltage and channel number, however this calibration must be performed. For alpha radiation, this calibration must be done in vacuum to avoid the energy loss of intervening particles. Similarly, the radioactive source used for calibration must be thin such that there isn't much self-absorption of alphas in the source itself. We have tested our detectors in vacuum with a thin film ^{241}Am source using both our amplifier/MCA apparatus as well as a commercial amplifier/MCA. We find a conversion of $G_1 = 0.264 \pm 0.001 \frac{e}{eV} = 0.264 \pm 0.001 \frac{C}{J}$ consistent over several photodiodes. The gain of the preamplifier/MCA can be calibrated using pulses, though we have found that using the nominal gain of the simple op-amp feedback circuits gives accuracy of a few percent. This amplifier calibration was done by the students during the first iteration of this experiment, however we intend to simplify the procedure for the upcoming fall term, since the experiment was too long for the time allotted. Using a well-calibrated detector to measure the spectra of other sources allows the propagation of this calibration to all the sources and detectors. For purposes of this exercise, a calibration of 0.4 keV/channel (for 16384 channels) can be assumed.

Two experiments are described here:

1. Measuring the energy loss as a function of distance in air, and
2. Measuring the energy loss as a function of mylar thickness.

Both cases start with a manual measurement of alpha energies using the oscilloscope function of the STEMlab and a lab-book histogram, followed by an introduction to the MCA software and measurement of a spectrum with the sample close to the detector.

Alpha spectrum measurement:

1. Connect the photodiode to the amplifier input to input 1 of the STEMlab through BNC cables. Connect +/- 15V and ground banana cables to the preamplifier, however do not power on at this time.
2. Being careful to **not touch** either the photodiode active surface or the americium source, open the detector box and place the source close (< 5mm away) from the photodiode. We use Lego to allow for a reproducible separation. Alignment of the diode with the source is critical.
3. Close the box containing the source.
4. Power on the amplifier.
5. Connect the USB power supply to the STEMlab and look for indicator LEDs to light up.
6. Connect to the STEMlab using your laptop, tablet or phone wifi. Each STEMlab has a label taped to it. Connect to the Wi-Fi spot titled "rpXXtoday", where XX is the number on the instrument and then enter the password by the same name, and then open the web page at 192.168.128.1. There are other ways to connect to these instruments that we use in class (using ethernet and the university's LAN) however this works well for the demonstration.
7. The STEMlabs can be reprogrammed in various ways, however for this experiment we will use the oscilloscope and multi-channel analyzer. Open the oscilloscope.

8. Using the oscilloscope we have the students measure the heights of 10-20 peaks from the alpha particles detected in the oscilloscope. The STEMlab oscilloscope works similarly to many digital storage oscilloscopes. Here we zoom in, set a positive trigger voltage, turn on peak-to-peak measuring and use single triggering to help the measurements.
9. When the measurements are done well enough, we ask the students to switch back to the STEMlab home screen, and open up the MCA application.
10. Set up the MCA to take positive pulses, sampling every 64 ns, with auto baseline and a threshold of 0 channels (to begin with). Take data for a short time and adjust the threshold to remove the spurious peaks at low energy. Take data until there are several hundred counts per channel at the peak. Export your data to CSV.
11. The calibration for the detector/amplifier/MCA system is approximately 0.4 keV/channel for the full 2^{14}=16384 channel mode, or 6.4 keV/channel for 2^{10}=1024 channels.

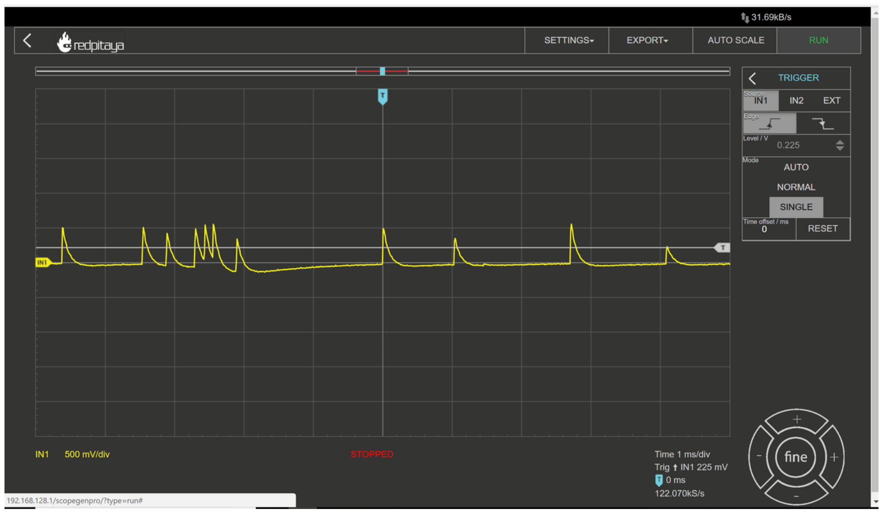

Figure 6: Amplified pulses from the ^{241}Am source as detected by the STEMlab oscilloscope.

For experiment 1: **Energy loss in air**

1. Repeat measuring the spectra as a function of distance between the source and the detector by moving and inserting lego blocks and plates. With care it is possible to have steps down to 1.2 mm in separation. The studs on Lego bricks are 8.0 mm apart, bricks are 9.6 mm tall and plates are 3.2 mm thick. The count rate drops significantly as the separation increases, both due to energy loss but also due to geometric effects.

For experiment 2: **Energy loss in mylar**

1. We use 2.5 micron thick polyester terephthalate films (mylar)(spi) attached to paper. Here we are able to measure the spectrum with up to 7 layers of mylar in between source and detector and measure the resulting spectrum.

Analysis:

We use Python through Jupyter notebooks to analyze the data. A sample notebook is available. To account for the straggling of the alpha particles we sometimes fit to a modified gaussian function, where each side of

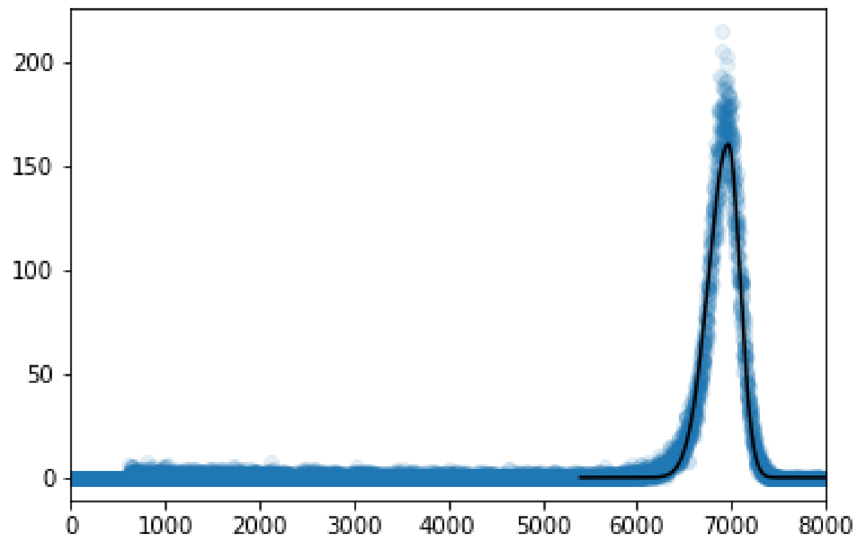

Figure 7: Histogram output from the STEMlab MCA for a smoke detector ^{241}Am source, with the accompanying best fit line to the spectrum. Clicking the </>Code tag next to the graph allows you to open the Python Jupyter notebook used to fit the curve, and allows you to upload your own data and use the same fitting functions.

the peak has a different width. To see an example worksheet, see the <code> block connected to Figure **??** in the online document, or the accompanying files.

We find, however, that there are large uncertainties in determining the stopping power from the data. This is likely due to too few data points in distance, giving increased uncertainties once a numerical derivative is done.

Discussion:

There are several limitations to the experiments done here:

- Smoke detector sources have significant self-absorption, due to the thickness of the coating, leading to a broadening and lowering of the energy compared to a source designed for alpha particle spectroscopy.
- The PIN photodiode and amplifier pair are far noisier than a professionally designed detector/amplifier, and do not include optimized pulse shaping.
- There are few options in the MCA software to deal with more complicated pulses or spectra.
- Measuring the energy loss spectra while moving the sample inherently brings in geometric effects which aren't present when changing the pressure for fixed geometry.
- The stopping power measurement depends on differentiating measured energy spectra with distance, and hence have large uncertainties.

However, these limitations do not obscure the learning outcomes of the experiment. For the first time at our university we can teach the basics of nuclear and particle physics simultaneously to 40 students.

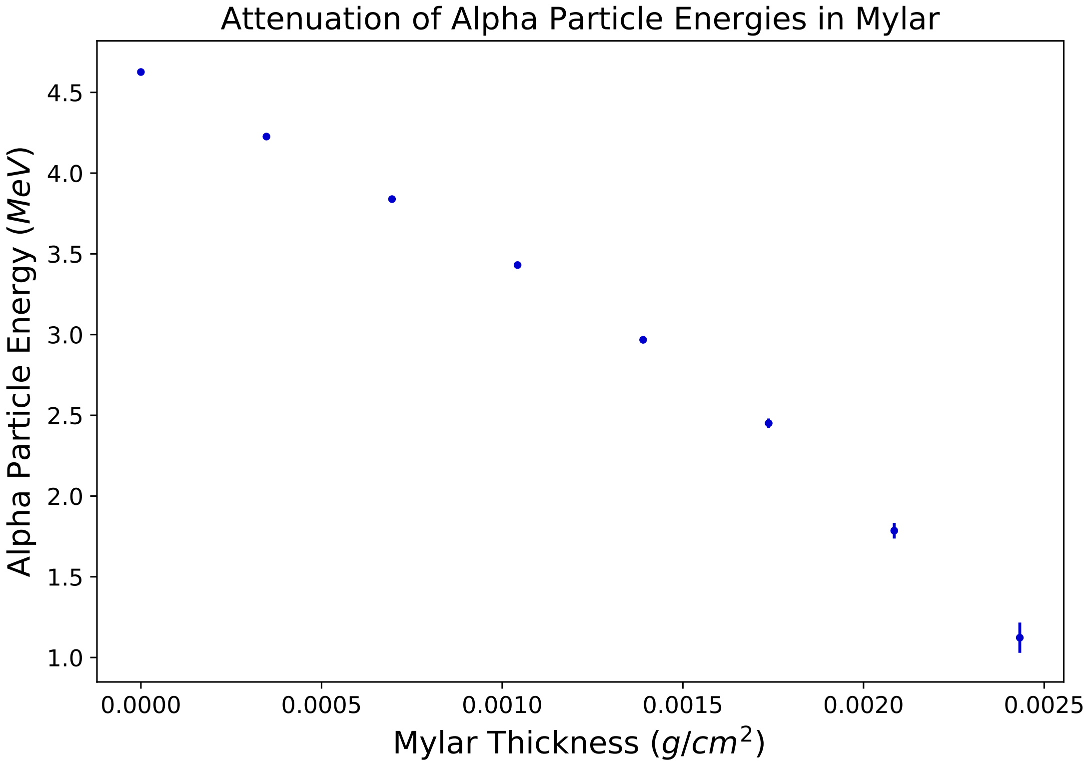

Figure 8: Example data of alpha particles attenuated by up to 7 sheets of 2.5 micron-thick mylar film.

Importantly for the design of our course as a whole, we have built reconfigurable op-amp amplifiers with performance far exceeding a similar circuit built on a proto-board. We also have 20 of the STEMlab instruments which have been used for experiments probing the quantized conductance in gold wires(Tolley et al., 2013), teaching LabVIEW by using a silicon diode as a thermometer, and in several projects in the latter part of our courses. We wanted to simplify the transition from set experiments to open-ended projects by giving students access to cheap, powerful and flexible instrumentation during the early part of the lab course. The first iteration of this course was a success, and we intend to extend this still more with subsequent deliveries.

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