The relevant appendices can be found under 'Related Documents' for each experiment at this link:
http://sky.campus.mcgill.ca/Exp/exp.a5w#

Alpha Decay

Updated in August 2018

Warnings:

- *Do not* change the pressure while the detector is biased!
- Each silicon detector operates up to a certain voltage and with a certain polarity that varies for each detector. *Do not* use the detector out of its range. In particular, operating with the wrong polarity will likely irremediably damage the detector. See Handling Precautions on page 10 for specific instructions.
- Ask for the assistance of a professor or a technician when using the Thorium flask to collect the radioactive source. **Important:** if you drop a collector disk in the flask, *do not* try to pick it up.
- Keep the Thorium flask covered except to insert or to remove the collector disk, which you must do with the supplied pliers.

You must follow a specific procedure to start and stop the electronics. To start:

1. Make sure that the bias voltage on the detector is 0V;
2. Start the pump and let the chamber reach a pressure under 200millitorr;
3. Slowly apply the bias voltage on the detector up the nominal voltage.

To stop:

1. Slowly return bias voltage on the detector to 0V;
2. Stop the pump and let the chamber reach atmospheric pressure by opening the valve.

Contents

1 Introduction

This experiment introduces you to the basics of nuclear spectroscopy through the study of some of the decay properties of nuclei involved in the decay of ^{212}Pb to ^{208}Pb. The lifetimes of two members in the decay series (^{212}Pb and ^{212}Bi) will be determined as well as the branching ratios in the decay of ^{212}Bi and the energies of the α-particles emitted during the decay. In addition, you will study the energy loss of the α-particles as a function of the pressure of the air they travel through to reach the detector.

2 Theory

2.1 Alpha Decay Properties

A more complete treatment is given in Appendices A and C.

The α decay in unstable nuclei corresponds to the ejection of a helium nucleus from the parent nucleus; a change of element is thus observed in the parent atom. Obviously, this release creates a mass and energy drop in the parent atom. Consider the ejection of an α-particle by some nucleus X; this may be represented by:

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}X'_{N-2} + \alpha $$

where A, Z and N represent the number of nucleons, the number of protons and the number of neutrons in the nucleus X, respectively. Conservation of energy in such a process yields the following equation:

$$ m_X c^2 = m_{X'} c^2 + T_{X'} + m_\alpha c^2 + T_\alpha \tag{1} $$

where the m's represent the masses of the indicated particles, c is the speed of light and the T's represent the kinetic energies of the indicated final particles. By rearranging, we get the release in energy Q:

$$ Q = (m_X - m_{X'} - m_\alpha)c^2 = T_{X'} + T_\alpha \ . \tag{2} $$

A spontaneous decay may only occur if $Q > 0$. Typically, the α particle carries about 98% of the energy release Q.

We may also predict Q by using the expression for the binding energy[1] B:

$$ B = a_v A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3} - a_{sym}\frac{(A-2Z)^2}{A} + a_p A^{-3/4} \tag{3} $$

where a_v, a_s, a_c, a_{sym} and a_p are constants; experimental data gives them values of 15.5MeV, 16.8MeV, 0.72MeV, 23MeV and 34MeV, respectively.

In our case, we might then expect that:

$$ Q = (B_{X'} + B_\alpha) - B_X \ . \tag{4} $$

Note that this equation gives an order of magnitude estimate; it is not expected to come in exact agreement with experimental data.

2.2 Decay of ^{212}Pb to ^{208}Pb

The decay series which we shall investigate is sketched in figure (1). ^{212}Pb decays by β-decay to ^{212}Bi. Roughly one third of the ^{212}Bi nuclei then decay via ^{208}Tl to ^{208}Pb, the first decay being one of four α-decay of varying energies and the second one a β-decay. The other two thirds of the ^{212}Bi nuclei decay to the same final isotope, ^{208}Pb, via ^{212}Po. Here, the first decay is by β-emission and the second one by α-emission. With your detector, only the α-particles will be detected; their energy and branching ratios are listed in table (1). More details on the decay properties of these nuclei are given in Appendix F.

[1] See Appendix A for a discussion of all the terms in the equation.

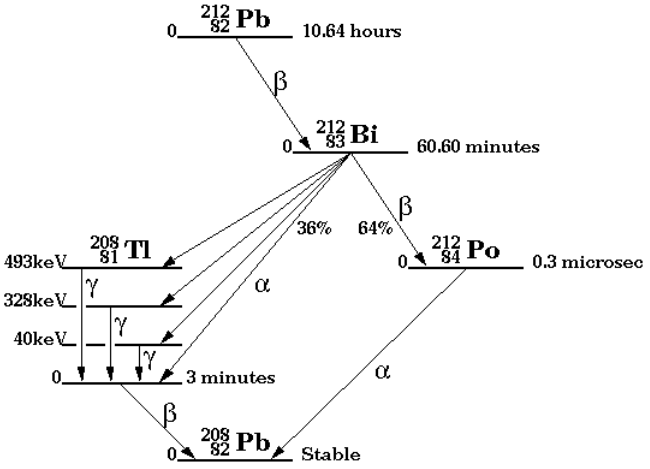

Figure 1: Scheme of the principal transitions in the ^{212}Pb to ^{208}Pb decay.

Transition	Branching ratio	α-ray energy (MeV)	Branching ratio of specific transition
^{212}Bi to ^{208}Tl	36.0%	5.607	1.10%
		5.769	1.67%
		6.051	69.9%
		6.090	27.2%
^{212}Po to ^{208}Pb	64.0%	8.794	—

Table 1: Energies and branching ratios of the alpha decays involved in the transition from ^{212}Pb to ^{208}Pb.

2.3 Half-life of Radioactive Isotopes from Measurements of the Activity

From the decaying rate (or activity), of the ^{212}Bi isotope, we may cleverly obtain the half-life of ^{212}Pb and ^{212}Bi. If $N_2(t)$ is the number of ^{212}Bi nuclei at time t, the activity of ^{212}Bi is given by

$$A_2(t) = \lambda_2 N_2(t) = \frac{N_0 \lambda_1 \lambda_2 (e^{-\lambda_1 t} - e^{-\lambda_2 t})}{\lambda_2 - \lambda_1} \tag{5}$$

This relation is derived explicitly in Appendix B. The subscripts "1" and "2" refer to ^{212}Pb and ^{212}Bi, respectively; N_0 is the number of ^{212}Pb nuclei at t=0 and λ_1, λ_2 are the decay constants as defined in section 6.1 of Appendix B; they are related to the half-life $t_{1/2}$ by $\lambda = \ln(2)/t_{1/2}$. Thus, a fit of the activity of the source over time can return the half-life of both isotopes. The relation is valid under the assumption that $N_2(t = 0) = 0$. Note, that for fitting the data, this is not a good assumption. You may solve the differential equations using $N_2(t = 0) = \text{const.}$; this yields an expression for the activity as given in equation (5) plus an additional term $\lambda_2 N_2(t = 0) e^{-\lambda_2 t}$ on the right-hand side.

Using the literature values for the half-life $t_{1/2}$ of the two isotopes of interest, you might want to calculate λ_1, λ_2 (see Eqn 6.3 of Appendix B) and then plot the expected time dependence of A_2. This will help you to decide on the time intervals over which you will record the activity. Further theory on the α-decay process is given in Appendix C.

3 Apparatus

The block diagram of the experiment is represented in figure (2) (model numbers may be different than those shown). The specifics of the various parts of the setup are to be described below.

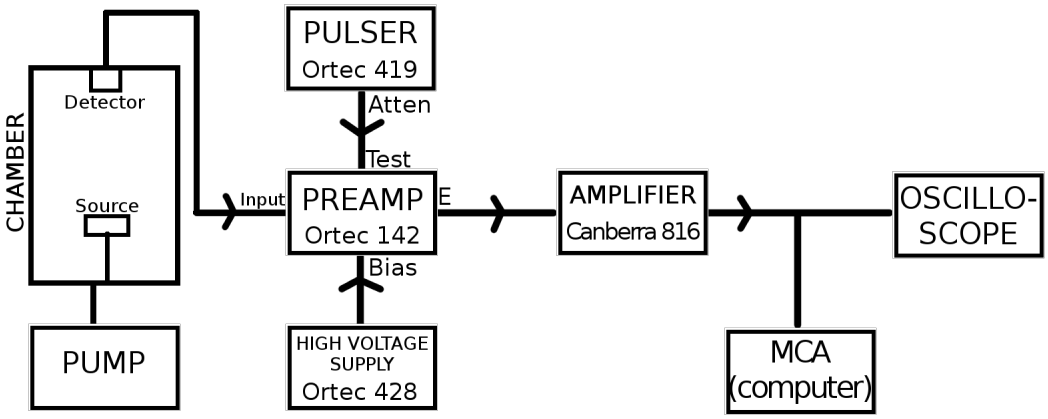

Figure 2: Block diagram of the experiment.

3.1 Chamber

The vertical chamber in which the experiment takes place is connected to a vacuum pump in order to evacuate it to reduce the interaction of the α-particles with the transiting environment. The pressure inside the chamber may then be read on a manometer connected to the pump.

Sources

As mentioned above, the source that you will study in this experiment is ^{212}Pb. This isotope has a relatively short half-life of about 10 hours, which is convenient for activity analysis over a relatively short period of time, but inconvenient as you will have to collect it yourself due to its fast decay. This is done by using a flask containing Thorium salts in the radioactive source locker - the procedure is highlighted below.

For calibration purposes and for the energy loss part of the experiment, you will use a ^{241}Am source, which has a lifetime of 432.6y and (in the resolution of this experiment) one strong α-peak at 5.485MeV. This source can be safely handled by hand.

Detector

The detector is a surface barrier detector. Its working principles are briefly described in Appendix D. In short, α-particles lose their energy in the detector, which is essentially a p-n semiconductor junction operated under reversed bias, by exciting electron-hole pairs (≈ 3 eV per excitation). The detector then sends the created charges through the electronics as a current pulse; the larger the energy is, the more electron-hole pairs are excited and the bigger the pulse is.

Before applying the bias to the detector, make sure that the correct polarity is set on your bias supply. This is not necessarily the same polarity as another Alpha Decay setup.

3.2 Electronics

As mentioned, the detector sends out a current pulse every time that it receives an α-particle from the source. The pulse is then converted to a more stable voltage pulse through the pre-amplifier, to which is also supplied a high-voltage bias. The pulser module is used uniquely for calibration or for setup testing - the calibration procedure will be detailed below. The pulses are then amplified - you may use a gain of around 32x4 (coarse x fine) as a starting point. The amplified signal is then sent to the Multichannel Analyzer (MCA), which is software installed on the given computer associated with your setup. The signal from the amplifier, which you shall split with a "tee", also goes in **CH1** of the oscilloscope for your viewing pleasure or for troubleshooting.

3.3 The Multichannel Analyzer (MCA)

The multichannel analyzer acts as a voltmeter and classes the input pulses individually in a number of bins depending on their amplitude. Basically, the particles coming from the source have a certain energy; when they hit the detector, they produce a voltage that is proportional to their energy; this voltage produces a current that is amplified by the apparatus; the MCA records the number of pulses with a voltage falling into different intervals, hence producing a histogram of the number of pulses received as a function of their voltage, which is proportional to the energy of the particle that produced them; using a proper calibration, one can thus obtain a histogram of the number of particles as a function of their energy. The MCA will be the MAESTRO software, in Windows. Here follows a short overview of the basic functions of both of them.

MAESTRO

MAESTRO is easily accessible from the Start Menu. Choose the right device in the shortcut bar.

- **(Alt-1) Acquire**: This starts the data acquisition. You should see counts accumulating in the bins of the graph (the MCB must be selected rather than the buffer). Pressing **Alt+2** stops the acquisition.
- **(Alt-3) Clear**: This resets all bins to zero counts for a new data acquisition. For this function to work, the acquisition must be stopped.
- **Scaling the graph**: You may scale the graph in both directions by using the "Display" menu.
- **Saving and loading datasets**: You may save your data acquisition in MAESTRO's native file format (.chn) and load it back later through the "File" menu..
- **Region of Interest (ROI)**: The ROI functions allow you to select a specific region of the spectrum to obtain its total number of counts. You will use them multiple times during the experiment. Select a region with the mouse, right-click and select "Mark ROI". The region will become highlighted, and the bottom of the window will show the number of counts in the region when the cursor is above it. The "net area" uses the rest of the spectrum to do an approximate removal of the background noise - be very wary of using the value it returns.
- **Job control**: The computer may divide a data acquisition in multiple segments of a given time, as you will have to do when measuring the activity of the source as a function of time. MAESTRO does this by using code stored in a .job file, which you may use through the "Job Control" function in the "Services" menu. You will need to copy this piece of code[2] in a text editor, replace the text in caps by the values you want to use and save it as a .job file:

```
; Batch Process to do three acquisitions and save to disk
; January 8, 2010
; Paste this code into a file called loop.job
; Replace text in caps by the value you want to use
; You may change the file name to prevent overwriting,
; however keep the ??? as they represent the iteration number of the loop.
set_detector 1
stop
set_preset_clear
set_preset_live TIME_ACQUISITION_PERIOD_IN_SECONDS
loop NUMBER_OF_ITERATIONS
        clear
        start
        wait
        stop
        save "file???.chn"
end_loop
```

[2]Which you may copy and paste for your convenience at `http://www.ugrad.physics.mcgill.ca/wiki/index.php/Alpha_Decay#Maestro_Software`

You may then follow the aforementioned steps to start the acquisition. You will notice that two time measurements appear on the display - the "elapsed" time and the "real" time. The latter is simply synchronized with the computer clock and returns the total number of seconds of data acquisition. The former also accounts for the "dead time". The computer, here, needs an analogous minimal time before it can register a second pulse after a first pulse arrives - this corresponds to a "dead time interval". The "elapsed" time removes these time intervals in order to get accurate counting rates in spite of this phenomenon - it is significant in experiments with very fast counting rates (such as the Compton experiment), and not-so-significant for experiments with lower counting rates (such as the Rutherford experiment or the present experiment). In the present experiment, where the counting rate is small, the effective dead time should be very small (less than a few %) and can thus be neglected.

3.4 Data Analysis Software

For the source activity part of the experiment, you will have to isolate a peak region in each of the spectra; this would however be very long and tedious, as a long run will give you a few hundred files to analyze. Thankfully, resident programming artist Mark Orchard-Webb has written multiple programs to perform a simultaneous analysis on a large number of .chn or .spm files. A description on how to use the programs for .spm files is given in Appendix G; for .chn files, simply replace the "spm" prefix by "chn" in the program names.

Alternatively, you may type `chn` or `spm` (depending on which Alpha Decay setup you use) in a Linux terminal, then press **Tab** to see what are the names of the various programs. To learn how to use them, you may then type `man program` (replace `program` by `chnread` or whatever program you want to study) in the terminal to fetch their instruction manual.

4 Experiment

4.1 Alpha Decay Properties

4.1.1 Energy Calibration

As mentioned earlier, the calibration involves the ^{241}Am source and a pulser. What you must do, here, is to obtain the relation between the channel numbers of the MCA and the α-energies. Place the source inside the chamber, screw the detector on its top disk and bring the chamber to a vacuum with a pressure below 200mTorr. You may now put a bias voltage on the detector (within the limits of its range!), then obtain a spectrum on the MCA. If the pulser is off, you should see a single energy peak - if you do not see it, try adjusting the amplifier gain. Once the peak is in sight, adjust the gain further to place it at about 60% of the top channel. The amplification and the bias voltage should not change for the rest of the experiment as this would change the calibration – the bias voltage being reset to the same value for each measurement.

Now, turn the pulser on. By setting an appropriate pulse height, you should see a second peak appear on the spectrum during the acquisition. You may then record the peak channel number with different pulse heights, then obtain the channel number/amplitude relationship by taking a linear fit. You must then convert the amplitude scale to energy. The linear fit gives you the zero channel of both the energy and the amplitude scale, as a pulser amplitude of 0V gives you an energy of 0MeV; the Americium source gives you another energy value which you can also associate to a channel number. You may then convert the channel scale to an energy scale by using those two points.

4.1.2 Preparation of the ^{212}Pb Source

The second step of the experiment consists in the preparation of the ^{212}Pb source. Before preparing a source, **make sure to get proper instructions from an instructor or a technician**. For this purpose, a collector disk is mounted in the upper part of a glass flask containing long lived Thorium salts. This flask is in the radioactive source locker, and you will have to ask an instructor or technician to open it for you. The collector disks are small brass pieces with a pin sticking out in the middle; they are provided in the experiment's drawer.

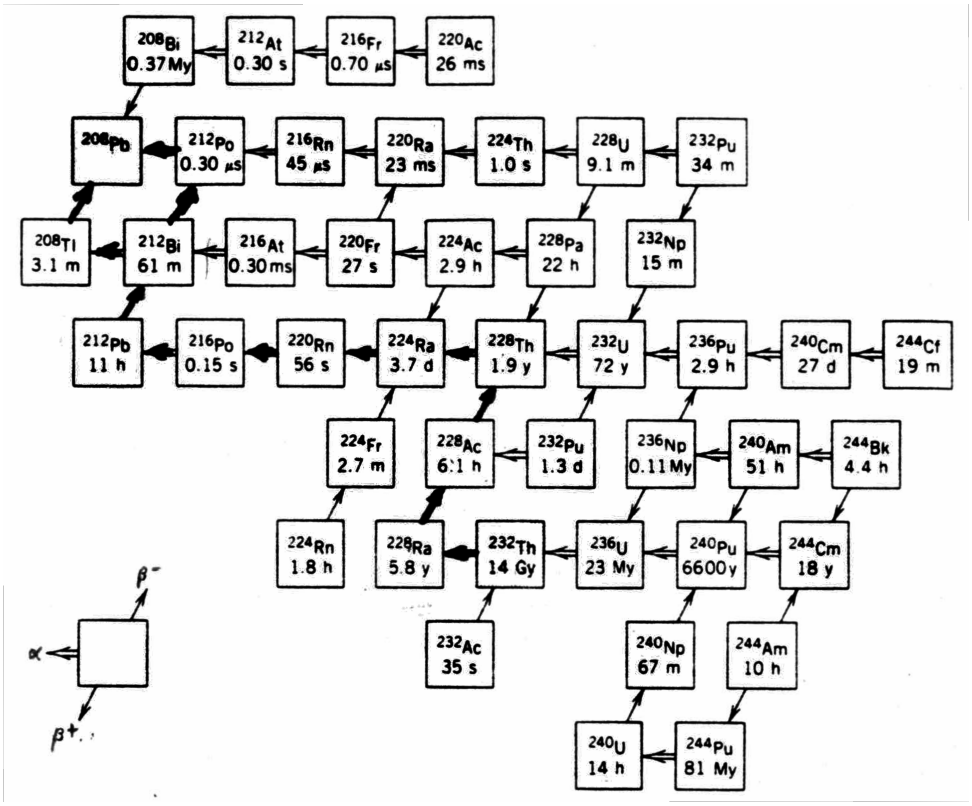

Figure 3: Decay scheme of ^{232}Th. The mechanism of interest is indicated with bold arrows. Taken from Krane, Kenneth. (1987) *Introductory Nuclear Physics.* Wiley. Third edition, Ch.6, p. 180.

The Thorium decays through a series of α and β-decays to ^{212}Pb (see figure (3)). The second to last decay product before ^{212}Pb is a short lived isotope of Radon. Since this element is a noble gas, it can diffuse out of the salts at the bottom of the bottle and build up a "cushion" above the salts. Then, α-particles emitted in the decay of various isotopes will ionize atoms in the Radon cushion. The resulting ions, which rapidly decay to ^{212}Pb, are attracted onto the collector disk by applying a potential difference between the Thorium salts and the collector. In our setup, the disk is kept at ground and the salts are positively biased to 1000V. You may use different collection times during the experiment; a minimum of 20 minutes should be taken, and you should at least do the experiment with one collection time on the order of an hour, and one on the order of a day.

4.1.3 Half-Life Measurement

Next, place the disk in the vacuum chamber, close the system and pump out to a pressure of p $\leq$ 100mTorr. **The detector has to be operated under vacuum** and then the mean free path of the α-particles will then be long compared to the distance between the source and the detector. The activity can then be measured for predetermined time intervals, as mentioned in the description of the MCA. The time intervals for the individual measurements of the activity should be short compared to the shortest lifetime involved in the decay but still long enough to get reasonable statistics in your recorded spectra (5 to 10 minutes per individual measurement has been appropriate in the past). The total time for the full acquisition should be longer than the longest half-life involved in the experiment (using a full day would be appropriate).

A plot of the activity as a function of elapsed time, which you can get by using the aforementioned programs on a Linux box, should then give you something resembling equation (5) - a rising curve followed by a decrease akin to an exponential decay. By performing a fit on the curve, you can extract the half-life of both ^{212}Pb and ^{212}Bi.

4.1.4 Energy of the α Emissions

You will need to determine the energy of the α-particles emitted in the decay process. This is done by using the same dataset as the last section. However, here, to have a sufficient dataset, you will need to sum all of the separate spectra you obtained over the full acquisition time. This can be done by using the `spmsum/chnsum` programs on the Linux boxes. You can then plot the resulting spectrum, on which you should see five peaks. You may perform this part of the experiment with the different collection times to see if there is a discrepancy.

You may then perform fits on the peaks in the spectrum to obtain the energy of the transitions; you will notice, however, that the peaks are quite asymmetrical, whereas you may expect a classical Gaussian shape - the part with lesser energy than the peak energy is more sizable than the part with greater energy than the peak energy. This happens as the particles may lose energy by a variety of interactions, but cannot gain energy during the transiting process. You will need to find a way to account for the asymmetry and still obtain reasonable fits. You may also need to reduce the contribution of background noise in some manner.

You may then compare the measured energy release, or Q-value as discussed earlier, to the energy release predicted by the binding energy formula (equation (4)).

4.1.5 Branching Ratios

Again, by using the same dataset, you may determine the branching ratios of the ^{212}Bi decay. This is done by simply taking the total number of counts of each peak present in the full spectrum and by dividing by the total number of counts. The difficulty, however, is that you will obtain a double-peak with the 6.051MeV and 6.090MeV α-energies. A wise way to isolate their individual contributions would then be to integrate their fits.

4.2 Energy Loss Measurement

4.2.1 Additional Theory

In traveling through any material, an α-particle loses energy to scattering by the atoms in the material. The interaction of charged particles with matter is discussed in Appendix E. The amount of scattering depends, to first order, only on the α-energy and on the amount of material traversed. One could imagine a table top experiment in which an α-source emits α-particles which traverse a distance x in atmospheric air and then enter a detector. The energy of the detected αs could then be studied as the source-detector separation x was varied, and we could obtain the mean rate of change of energy with respect to distance, $S = - < dE/dx >$, defined as the **stopping power** S of the medium. It is convenient to define the target thickness, $t(x)$, in g/cm^2, which is simply given by:

$$t(x) = \rho_{air} x \tag{6}$$

where ρ_{air} is the density of air at room temperature and atmospheric pressure.

A technical problem with the above experiment arises because the source and detector are not located at a single point. Because of their finite area, the solid angles subtended by both pieces vary as the separation x changes. The experiment is modified, therefore, by keeping the separation x constant and varying the air density ρ_{air}, and therefore the target thickness $t(x)$. Since x is now constant, all the solid angles remain fixed. The air density ρ_{air} is varied by changing the pressure P_{air}. In a chamber of volume V filled with N moles of a gas with molecular weight M_{air} at a temperature T_{air}, the ideal gas law predicts that:

$$P_{air} V = N R T_{air} \tag{7}$$

where R is the ideal gas constant. Since the bulk density is given by $\rho_{air} = M_{air} N/V$ we can simply determine the target thickness of the air, $t(x, P)$, as:

$$t(x, P) = \rho_{air} x = \frac{M_{air} N}{V} x = \frac{M_{air} P_{air}}{R T_{air}} x \tag{8}$$

This equation shows that, in fact, increasing the pressure P_{air} or increasing the separation x by the same factor should have exactly the same effect on the target thickness $t(x, P)$. The molecular weight of air is about 29g/mol. Combining this with the definition of the stopping power yields:

$$S = - < \frac{dE}{dx} >= - < \frac{dE}{dt}\frac{dt}{dx} >= -\rho_{air} < \frac{dE}{dt} >= -\frac{M_{air}P_{air}}{RT_{air}} < \frac{dE}{dt} > \tag{9}$$

4.2.2 Procedure

You may then obtain the stopping power S by varying the pressure inside the chamber and by recording the energy for each new pressure. This is done with the ^{241}Am source as it has only one peak (in the resolution of this experiment). By pumping full out on the chamber and by adjusting the regulator valve, you should be able to stabilize the chamber pressure between $\approx$ 0mbar and $\approx$ 1000 mbar to within 1mbar or so.

Always power down the detector before changing the chamber pressure. The manufacturer warns that changing pressure with the detector powered up may cause irreversible damage.

After stabilizing the pressure, power up the detector and collect an α-peak. Note the α-energy, E, at which the peak occurs. You may also want to measure the peak width and the peak intensity, to see if the same number of α-particles is reaching the detector regardless of the pressure.

Perform the experiment for at least fifteen equally spaced pressures and be sure to measure x, the separation between the α-source and the detector. From the measured pressures and the above equation, you can now determine the value of t. Plot the α-energy E against t. You can also approximate the energy loss as $< dE/dt >= (E_1 - E_2)/(t_2 - t_1)$ and determine the mean target thickness, $\bar{t} = (t_1 + t_2)/2$, for adjacent points. Plot the stopping power in MeV$\cdot$cm^2/g vs $\bar{t}$ in gm/cm^2. Can you predict from this plot that a 5MeV α will be stopped in about 4cm of room temperature air at atmospheric pressure?

5 Goals

In short, you must:

- Calibrate the energy scale of the MCA by using the ^{241}Am source;
- Determine the half-life of ^{212}Pb and ^{212}Bi by recording the activity of the source multiple times over some time period;
- Measure the energy of the α-particles involved in the decay from ^{212}Pb to ^{208}Pb and compare your results to the prediction of the binding energy formula;
- Determine the branching ratios of the ^{212}Bi decay from the area of the individual peaks;
- By using a ^{241}Am source, obtain the stopping power of the air by changing the pressure in the chamber and recording the α-energy for each of them;
- (optional) Expand on the experiment however you can! You may for instance estimate the rate of collection of ^{212}Pb in the Thorium flask.

Good luck!

Minor Changes by Liam Halloran, Aug. 2018
Updated by Gregory Bell in May 2017
Updated by Guillaume Huot in May 2016

HANDLING PRECAUTIONS FOR EG&G ORTEC CHARGED PARTICLE DETECTORS

- **Avoid mechanical shock.** Silicon fractures easily. Damage to the epoxy-silicon interface will destroy the contact structure of the silicon diode.
- **Never touch the gold electrode on the sensitive surface.** Damage to this surface will destroy the diode characteristics of your silicon detector. Keep the protective cap in place when the detector is not in use. A gentle air stream from a clean rubber syringe may be used to remove dust or lint.
- Do not expose the detector to reducing atmospheres, such as hydrogen gas.
- Apply bias only through a large ($\geq$ 1 megaohm minimum) series resistor. **Do not apply bias in excess of the rated operating voltage.** Do not apply excessive bias to the detector, nor allow it to operate under breakdown conditions. Unless you are adept at recognizing the onset of microplasma and are willing to risk destroying the diode, do not apply bias in excess of the rated operating voltage. [...]

Workstation	EQ	Bias Polarity	Operating Bias Voltage
Alpha I	EQ2613	(+)	65V
Alpha II	EQ2612	(+)	65V
Alpha III	EQ0448	(-)	100V

Follow these steps when applying bias to a detector:

- *Apply 10 to 20 volts to the detector.* The noise, as observed on an oscilloscope or noise meter, should decrease (assuming a low noise charge sensitive amplifier configuration is used).
- *Continue to increase the voltage in small steps, allowing the noise meter to recover from transients to a reasonably steady reading before making further increases in voltage.* Frequently, the noise will continue to decrease slowly for a period of several minutes to several hours; this is normal, particularly for detectors which have not been recently used.
- *Sudden momentary increases in the noise pulses are an indication of incipient microplasma.* If this phenomenon occurs, proceed very slowly, and if the frequency and/or intensity of noise pulses increase, reduce the bias by approximately 30 percent and allow the detector to "age" (for a time sufficient to permit increases in the bias level without the strong pulsing noise effect) before proceeding.
- A sudden, very large increase in noise, usually accompanied by an increase and/or fluctuations in the reverse current, is an indication of complete microplasma breakdown. Remove the bias voltage immediately in order to minimize irreversible damage to the detector.
- After the desired bias voltage is attained, observe the noise level for a short time, in order to determine that it is not increasing and that there is no incipient microplasma breakdown.

  Do not change the pressure around the diode suddenly while high bias voltage is applied. The preferred procedure is to pump down or let up, slowly, with no bias voltage applied to the detector. If the detector is stored for an extended time in vacuum, it is best to leave a small nominal bias applied even when not in use.

  The pressure region from ten μm to several millimeters of Hg is a particularly serious one for surface breakdown. Neither the connector nor the diode is warranted for high voltage in this pressure region. [...]

Written by Robert Turner, Aug. 2018