Alpha Ray Spectroscopy

1. Introduction

In radioactive **α decay**, a nucleus with Z protons and a total of A nucleons decays to a lower energy state with (Z-2, A-4) by emission of an "α particle", a tightly bound nuclear fragment comprising 2 protons and 2 neutrons. Many heavy radioactive nuclei are members of alpha decay chains, where a succession of these decays takes an unstable nucleus through a number of unstable intermediate states on the way down to nice stable heavy, like lead. It was in the study of these processes that Rutherford became the first person to observe the alchemists dream of "transmutation of the elements".

In this experiment, you will measure alpha-ray energies with a "solid state" particle detector. Using a small sample of Po^{210}, which emits a single alpha line, you can study the basics of the detector response, and establish an energy calibration. With a calibrated detector, the remainder of the lab is two separated studies:

a. The practical matter of the **energy loss of charged particles in matter** is studied by measuring the alpha particle energy as a function of the air pressure in the detector, converting this into a measure of energy loss per effective distance in air. This is compared to the classic theory of dE/dx and total particle range. This part of this experiment is described in great completeness in **Melissinos, Sec. 5.5.3.**

b. The nuclear physics of the **alpha-decay sequence** is studied by resolving several separate lines in the spectrum of Th228. This line energies can be related to the mass differences between the intermediate nuclei in the Th228 sequence, and the areas of the peaks to the relative populations and thus the half-lives of intermediate species. If time permits, study of the Th228 spectrum *vs*. pressure gives further information about dE/dx *vs.* E.

2. Alpha Rays

Find a good summary of nuclear physics and read it: Many "modern physics" texts include a chapter level summary discussion of nuclear physics, **Eisberg and Resnick (Chap 16)** or **Tipler** are particularly good. The classic reference is still **Evans,** which is surprisingly accessible.

In Bohr's model for atomic line spectra, an electron makes a transition between quantized energy levels, and the energy lost by the electron appears in a photon of specific frequency. Although we tend to think of this as a change in state of a single electron, it is useful to think of the process as a change in the configuration of the whole atom: the nucleus and its collection of electrons find a lower energy state, and the excess energy is carried away by a photon.

Now consider the nucleus, a multi-particle collection of protons and neutrons held together by the "strong" interaction, whirling about themselves in bound configurations with stationary wave-functions and quantized energies. There is no fixed attractive center (the nucleus does not have nucleus!), but the net effect of all the nucleons is to create an average nuclear potential in which the bound states of the individual nucleons are arranged in a shell scheme reminiscent of atomic structure. The configuration of all of the nucleons in this level structure is a collective nuclear state with a quantized energy. For large nuclei, the spectrum of the multi-particle states can be very complicated. In addition, with two different kinds of fermions, the Exclusion Principle allows 4 particles in each state, and changes of state can therefore include changes in particle identity.

a. The Curve of Binding Energy

The strong interaction is independent of charge: the strong force between a neutron and a proton is the same as that between two neutrons or two protons. However, the electric Coulomb repulsion between the like signed protons is still there, and a net destabilizing force for the nuclear state. This is the reason that $A > 2Z$ when Z is large: the excess of neutrons contributes enough strong binding energy to overcome the large internal Coulomb repulsion. This trend is evident in the famous "curve of binding energy", which shows the average binding energy per nucleon as a function of the atomic weight.

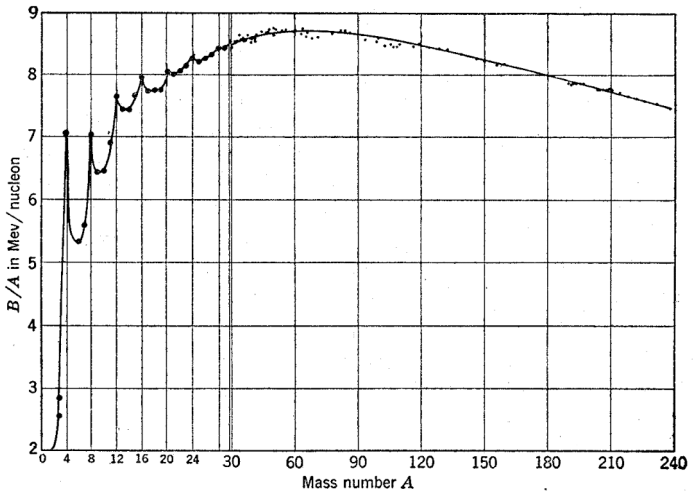


Figure 1. Binding energy per nucleon as a function of atomic mass. Note the change in horizontal scale at A=30. (Evans)

At low A, the addition of nucleons leads to a net increase in binding. At the hot centers of stars, the thermal energy is sufficient to push nuclei and nucleons together past the net Coulomb repulsion. This lead to the building up of complex nuclei from hydrogen; the binding energy is released as heat and light. The details of the nuclear force (particularly a strong spin dependence) lead to certain preferred configurations, akin to closed shells in atomic physics, such as the tightly bound helium nucleus, A=4, a.k.a., the α particle. Above iron, the binding trend turns downward. Stars thus burn nuclei up to iron, whereupon the burning stops, and if the mass is sufficient, gravitational collapse leads to a supernova explosion, where all the elements heavier than iron are made in the intense nuclear flux.

As the curve shows, for nuclei above iron, it is energetically favorable to move to a smaller value of A. This happens in nature by emission of an α particle, which reduces the Coulomb repulsion in the

remainder nucleus and gains an additional binding energy contribution from the tight binding at A=4. This is **α decay.** The decay happens specifically through the A=4 state because of its tight binding.

For the "two body" decay ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$, the energy liberated is

$$Q = \Delta E = \Delta M c^2 = (M_X - M_Y - M_a)c^2$$

Or, more conveniently, we can use masses in atomic mass units (amu):

$$Q = (M_X - M_Y - M_a) \bullet 931.5 \text{ MeV/u}$$

Using conservation of energy and momentum for the two-body decay allows calculation of the final α energy.

b. Alpha Decay as Barrier Penetration

So, why don't all the heavy nuclei just fall apart in this way? Think of the X nucleus before decay as a "virtual" superposition of the alpha and the Y nucleus, and consider the potential energy of the alpha as a function of radius. As long as the alpha is "inside", it sees the deep nuclear potential. But the nuclear force cuts off quickly at the nuclear radius, and an alpha particle just beyond the nuclear edge , at a distance $\sim 10^{-13}$cm would see the nuclear attraction go to zero and the large Coulomb repulsion due to the positive charge on Y. For a positive particle approaching the nucleus from the outside, this Coulomb barrier prevents the particle from getting in. For a positive particle approaching the nuclear edge from inside, this barrier prevents it from getting out!

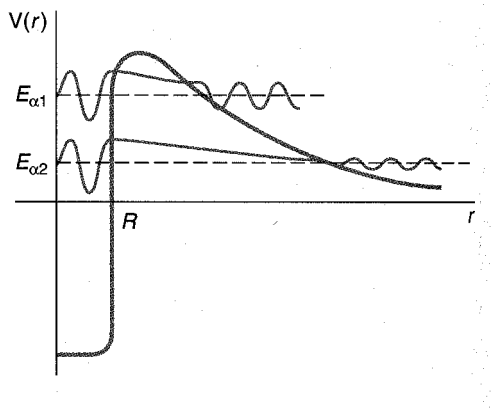


Figure 2 Tunneling at the Coulomb barrier. (Tipler)

However, in quantum mechanics, a particle can "tunnel" out of a classically forbidden region. As shown in Fig. 2, the wavefunction does not cut off at the edge of the well, but decays exponentially in the forbidden zone. The small positive amplitude left at the edge of the zone gives the probability of finding the particle "outside". The tunneling probability for a rectangular barrier is a standard problem in beginning quantum mechanics, and you should review it if you have done it, or look it up in the references. Using the Coulomb form for the barrier, this was first worked out as a model for alpha decay by Gamow in 1928, and gives reasonable values for the alpha nuclei half-lives. (A nice discussion is found in Eisberg and Resnick, sec 6.4-6.6).

c. Alpha Decay Sequences

In many cases, the nucleus left after an α–decay is itself unstable, leading to an α–decay sequence, as seen for the Thorium series in Fig. 3. We tend to think of this as a trip though various distinct elements as arranged in the periodic table; however, an alternative interpretation is that the entire chain is a set of metastable excited states of the final nucleus. In this view, Fig. 3 shows a set of excited states of lead, and the energies of the α's are simply the corresponding *line spectra* as the excited states decay to the ground state, as in atomic physics.

Many of the intermediate states have short half-lives, relative to the age of the earth, and would not exist now, except that ongoing decay sequences starting from long-lived states are continually replenishing the supply. The relative populations of all the states in the sequence are determined by the "related-rate" problem involving all of the half-lives, and the steady state solution is known as *secular equilibrium.* A sample will be in secular equilibrium after a time long compared to the longest lifetime In the decay chain.

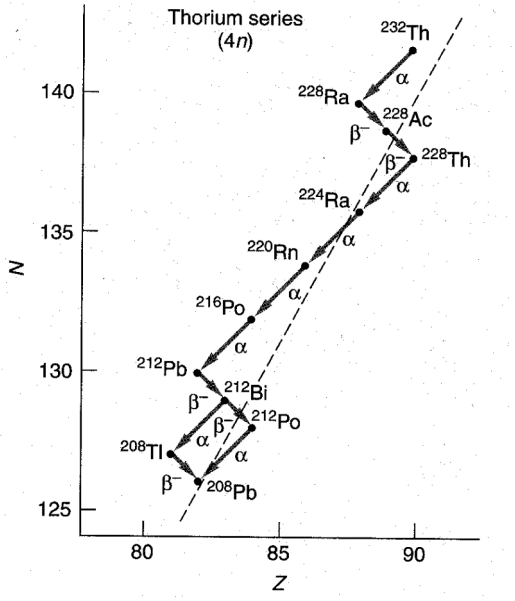


Figure 3 The 4n series which includes Th^{228} (Tipler)

2. Interaction of Charged Particles with Matter

You will detect α–rays by converting their energy to an electrical signal. The first step in this conversion is ionization.

a. The Rate of Energy Loss or "Stopping Power"

A charged particle passing through bulk matter loses energy by ionizing the atoms in its path. Each ionization is the result of a peripheral inelastic collision, and the process can be treated statistically to derive an average energy loss per unit length. As first worked out by Neils Bohr, for the case where the projectile energy is large compared to the ionization energy, the energy loss rate is

$$-\frac{dE}{dx} \simeq \frac{4\pi z^2 e^4}{m_e \mathrm{v}^2} \mathrm{N_e} \ln\left[\frac{m_e \mathrm{v}^2}{\bar{\mathrm{I}}}\right]$$

where z and v are the charge and velocity of the projectile particle, and N_e and $\bar{I}$ are the density of electrons and average ionization potential in the target material. The derivation is straightforward and elegant, and you should check it out in the references. The essential conclusions are that the rate of energy loss is proportional to the local density of electrons and the square of the projectile charge, and inversely proportional to the projectile energy.

The density of electrons is Z times the density of atoms, which is simply related to the mass density, thus

$$\mathrm{N_e} = \rho \frac{\mathrm{Z}}{\mathrm{A}} \mathrm{N_0}, \text{ where } \mathrm{N_0} \text{ is Avogadro's number}$$

The Bohr formula can be rewritten as

$$-\frac{dE}{dx} \simeq \frac{4\pi z^2 e^4}{m_e \mathrm{v}^2} \rho \frac{\mathrm{Z}}{\mathrm{A}} \mathrm{N_0} \ln\left[\frac{m_e \mathrm{v}^2}{\bar{\mathrm{I}}}\right]$$

b. The Mass Thickness

Since the ratio Z/A is approximately constant, and the ionization energy appears only in the logarithm, the strongest dependence of dE/dx on the target material is through the target density. This makes sense: the projectile slows down fastest in dense materials. However, it is a trivial sort of dependence, and it is useful to factor it out, giving

$$-\frac{dE}{d\xi} \equiv -\frac{dE}{d(\rho x)} \simeq \frac{4\pi z^2 e^4 \mathrm{N_0}}{m_e \mathrm{v}^2} \frac{\mathrm{Z}}{\mathrm{A}} \ln\left[\frac{m_e \mathrm{v}^2}{\bar{\mathrm{I}}}\right]$$

where $\xi = \rho x$ is the **mass thickness**, with units of g/cm^2. Expressed in this way, the energy loss formula has a certain universal behavior, to first order independent of the material, and depending most strongly on the velocity of the projectile. The mass thickness is frequently the experimentally convenient variable. For instance, in cosmic ray physics, given a flux of cosmic rays per cm^2 incident on the top of the atmosphere, the flux in a given cm^2 at the earth depends on the total amount of air in between, which depends on the total mass of air in the column. The actual path length is irrelevant, since the density is changing as a function of altitude. What you really want to know is the mass, *e.g.,* g/cm^2 of air. Sometimes the symbol x is maintained in the formalism with the implicit understanding that the units are g/cm^2; be careful about this.

c. The Bethe-Bloch Formula

Bohr's theory of energy loss was worked over by Bethe and others to account for the complications of quantum mechanics and relativity; this finally resulted in the famous **Bethe-Bloch formula:**

$$-\frac{dE}{dz} \equiv -\frac{dE}{d(\rho x)} \simeq \frac{4\pi z^2 e^4 \mathrm{N_0}}{m_e \mathrm{c}^2 \beta^2} \frac{\mathrm{Z}}{\mathrm{A}} \ln\left[\frac{2 m_e \mathrm{c}^2 \beta^2 \mathrm{Q_{max}} - 2\beta^2}{\bar{\mathrm{I}}^2 (1-\beta^2)}\right]$$

where Q_{max} is maximum energy transfer from an electron to the alpha. This equation predicts the behavior shown in Fig. 4 below. The curve is steep at low energies, but flattens out above $\beta\gamma \sim 5$, where all particles are "minimum ionizing particles", with an approximately universal rate of energy loss of $-dE/dx \sim 1\text{-}2$ MeV per g/cm^2, in all materials.

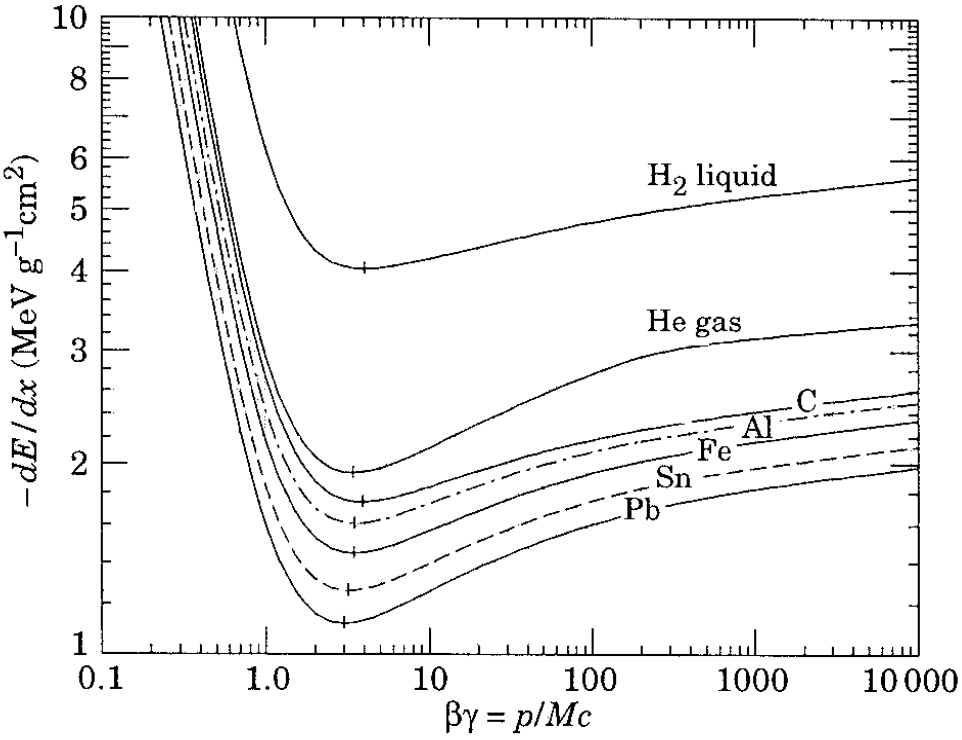


Figure 4 The Bethe-Bloch curves (from the Particle Data Book)

d. The Bragg Curve and the Range of Charged Particles

The dependence dE/dx ~ –1/E expresses the fact that slower particles spend more time in the vicinity of the atomic electrons and can ionize them more readily. Thus, as the particle is slowed by ionization losses, it loses energy faster and faster. The rate of energy loss is greatest at the very end of its trajectory. This is seen clearly in the famous Bragg Curve of -dE/dx *vs.* x, Fig. 5 , where dE/dx is seen to rise sharply just as the particle is about to "range out".

The total range R of a charged particle of initial energy E_0 in matter follows from integration of the stopping power. One finds:

$$E_0 = \int_0^R \frac{dE}{dx} dx \quad \Rightarrow R = \frac{\mathrm{M}}{z^2} \frac{\mathrm{A}}{\rho \mathrm{Z} \mathrm{N}_0} f(\beta_0^2)$$

$$\text{or } R_\xi \equiv R\rho = \frac{\mathrm{M}}{z^2} \frac{\mathrm{A}}{\mathrm{Z} \mathrm{N}_0} f(\beta_0^2)$$

Note that the range is also conveniently expressed in units of mass thickness. It grows with the mass and initial velocity, but falls as the square of the particle charge. Particle ranges *vs.* energy are well measured for many materials, and catalogued in the references.

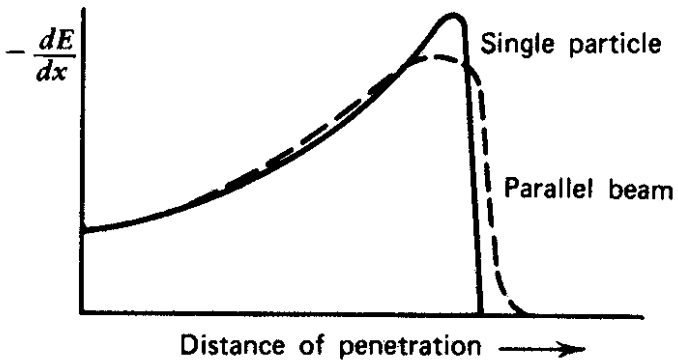


Figure 5 Schematic representation of the "Bragg Curve", the mean rate of energy loss per length, as a function of the distance. Notice that the rate of energy loss is highest near the end of the range. From Knoll.

3. The Detection and Measurement of the Alpha Energy

One way to detect α's would be to let them pass through a gas between the plates of a capacitor. In the electric field of the capacitor, the electrons and ions created by the α would drift to the plates, and be recorded as a current pulse. This is called, appropriately, an ionization detector. This idea works, but it is limited in practice by the fact that the current or voltage signals are very small, so that sensitive electrometers, careful control of grounding, *etc*. are required to measure it. A better technique is to build a semiconductor analog of the ionization chamber, measure the pulses with a charge-integrating amplifier, digitize the pulse heights, and send to a histogramming program. We outline the basic ideas below; further detail is given in the discussion of procedure in Sec. 4.

a. Solid-State Detectors (Required Reading: Leo 10.1-10.5.)

In a semiconductor, the equivalent of the ionization energy is the band-gap energy to promote an electron from the valence to the conduction band. In Si at room temperature, E_g = 1.1 eV, compared to ~15 eV to ionize a gas. A charged particle moving through Si therefore creates more ionization and a larger signal.

When n-type and p-type silicon are put in contact, creating a p-n junction, the flow of the two different free charges across the boundary creates a *depletion zone,* an electrically neutral area near the junction where an internal electric field sweeps out any free charge. By reverse biasing the junction, the depletion zone can be made large, ~ hundreds of microns. If an energetic charged particle ranges out in the depletion zone, an amount of ionization proportional to the particle's initial energy will be created there, and swept out. By plating metallic *ohmic* contacts on the outer surfaces of the crystal, it is possible to both apply the bias *and* collect the free charge from the depletion zone, so that the whole assembly is a high gain, solid state version of the capacitive ionization chamber.

In practice, the solid-state capacitor trick can be accomplished in a simpler way with a **surface barrier detector.** Here, a layer of metal, such as gold, is plated onto n-type silicon. The *contact potential* creates an electric field at the boundary, and the interface, called a *Schottky barrier* that has many of the same properties as a p-n junction and a depletion zone that can be made millimeters thick

This experiment uses a surface barrier detector. It reaches full depletion at a reverse bias of about 40 V. Note that a small amount of leakage current flows at reverse-bias, even without a source. A small part of this is from defect "recombination centers" in the detector, but most of it is typically due to unwanted surface films with high, but non-infinite, resistance, which conduct small amounts of wayward current around the detector. This can be minimized by keeping the detectors clean. With a source in place, the reverse current should be dominated by the average value of the ionization current.

b. **Modular Electronics**

You can find more detail in Knoll, Chapter 4. Briefly, the issues in our setup are as follows. The charge signal from the barrier detector is collected with a charge-integrating preamplifier. The charge on the detector flows into an operational amplifier with a large capacitance in the feedback loop so that the charge signal is converted to a voltage signal. The large capacitance of the amplifier insures that the capacitance of the detector, which varies with bias voltage and temperature, does not affect the charge-to-voltage gain. This signal is sent to a linear amplifier with RC-CR pulse shaping: the signal is differentiated to remove baseline shifts, and then integrated to remove high frequency noise. Some of the meanings of this will become clear when you look at the real signals below. The time-constant of the RC-CR circuit is called the "shaping time", and sets the ability of the apparatus to resolve pulses close together in time. The overall amplification allows increased resolution in the electronics for small energy differences, but the contributions to the resolution from noise are amplified as well.

Finally, the amplifier output is sent to an analog-to-digital converter (ADC) in the small black box, and the output of that is sent over the serial bus to the computer, which runs software with the plotting, histogram, and analysis package. It's a pulse-height-analysis: PHA. In the pre-computer days, the histogram function was done in hardware with a special purpose instrument like a big oscilloscope, which could record data in many channels (remarkable at the time), and hence was called a Multi-Channel-Analyzer. The jargon MCA has stuck, and that's why our device is called a "Pocket-MCA".

For testing and calibration, we will also use a pulser, which outputs voltage pulses of controllable magnitude. The modularity of the electronics allows you to insert these test pulses into any stage of signal chain.

4. Experimental Procedure

a. Preliminaries

First become familiar with the use of the oscilloscope, pulser, and pulse height analyzer (PHA). Note that all of the modular electronics expects output signals to be terminated in 50-100 Ω. If you plug the boxes into each other, you are fine. If you plug into the oscilloscope, which is high impedence looking in, you need to add a 50 Ω termination in parallel using a "tee" connector.

Connect the Ortec 480 pulser attenuated output to the oscilloscope with 50 Ω termination, and examine the pulses while varying the pulser amplitude, polarity, and attenuation. At the same time become familiar with the oscilloscope controls, including the voltage sensitivity, time scale, and triggering. Note the pulse height, pulse width, rise time and decay time.

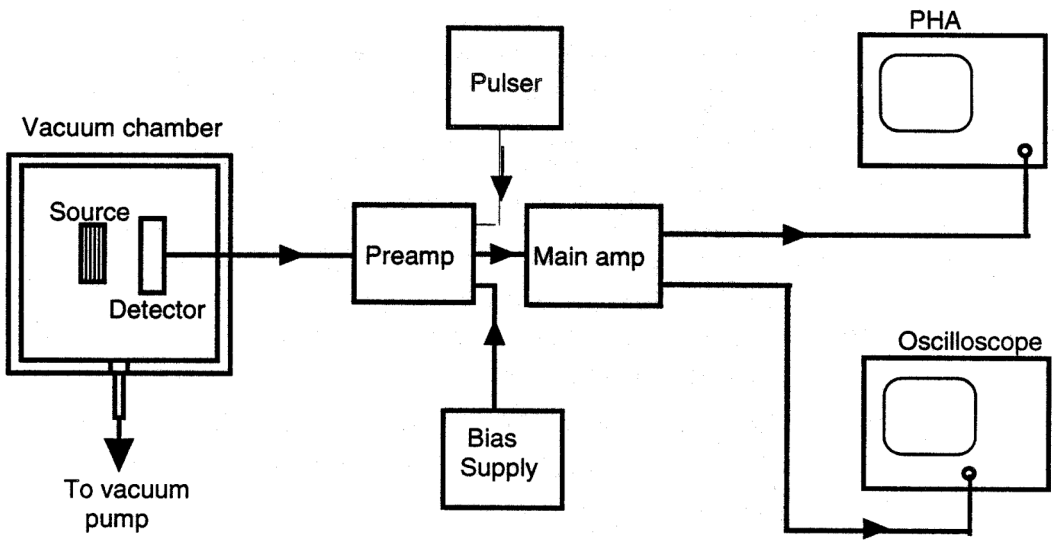


Figure 6 Block diagram of the experimental set-up.

The preamp is powered via a cable with a 9-pin connector that goes to the back of the 485 amplifier. Connect the pulser output to the preamp **test** input, and observe the output signal. Verify that you understand the preamp gain. With the pulser still driving the test input, plug the preamp output into the 485 amplifier input and observe the amplifier output signal with an oscilloscope. Become familiar with the amplifier controls. Compare the output (unipolar and bipolar) with the input signal.

Plug the amplifier output into the cable going to the Pocket MCA and, using a tee., to the oscilloscope input. Set the pulser/amplifier combination to give a unipolar output of about +6 V. Log onto the PC. Find the folder "MCA8000 WIN32" and run the application PMCA. You should get a standard Windows application screen with a large space for the histogram and, on the right, a column for display of counting statistics. When you start up, you will be asked whether to open an old data file, or connect to an MCA. Chose connect. You should hear the Pocket MCA start up. You may get a stale spectrum from the last measurement. On the banner, go to MCA, then "delete data", which clears the spectrum, and "reset time", which clears the counting statistics. Set the "MCA Gain" to 2048 and the Threshold to ~40. The small switch on the MCA should be set to the "10 V" position. Now do a "start acquisition", and you should see a narrow peak growing at a channel corresponding to the pulse height coming out of the amplifier. Vary the input pulse height, and watch the peak location change. [If the MCA hangs up with the hourglass symbol, do a ctrl-alt-delete and use the Task Manager to kill the process.]

b. Measurement of ^{252}Cf Spectrum and Calibration of Energy Scale

A solid state (silicon) detector is used to detect α/s from a radioactive source. The α's deposit all their energy in the silicon, and the charge from the detector is proportional to the energy of the α. The easiest way to calibrate the energy scale is to use a known α energy. The measurement must be carried out in an evacuated chamber since even a few mm of air will cause a significant energy loss of the α's, as you will study in the second part of the experiment. A bias voltage for the solid-state detector is fed to the detector through the preamp. **The detector is light sensitive (why?) so it is necessary to put the opaque cover over the lid to shield the detector from light**

i) ^{252}Cf Spectrum

Obtain a low activity californium α source (^{252}Cf). [Be careful in handling the source, as it is mounted on a very thin film and is very fragile.] Mount it as close as possible to the solid-state detector as shown in Fig. 6. Make sure the front side of the source is facing the front side of the detector and the source is well aligned with the detector. Put the lid back on. Open the valve between the vacuum pump and chamber, and close the valve which bleeds air into the chamber. Turn on the vacuum pump and press firmly around the edges of the lid to seat the lid against the O-ring. The vacuum gage should show the pressure decreasing rapidly. Connect the detector output to the preamp input (remember to remove your test input from the pulser!) and look at the output of the preamp with the scope. You should see a rather well defined grouping of positive pulse heights ~several millivolts from the α's, plus some very small pulses due to detector and amplifier noise. Note the size of the pulses, width, *etc.*

Check that the vacuum is below about 5 mm. Raise the bias voltage slowly while observing the pulse height and noise. Do not exceed 40 V bias.

Connect the output of the preamp to the input of the main amplifier and run its output into the scope and MCA inputs as before. Set the gain to give a unipolar positive output signal of about 6 V. Make a plot of the α pulse height *vs*. bias voltage. As the bias is raised, more and more of the charge produced in the detector is collected. At bias voltages >30 V or so, essentially all the charge is collected and the pulse height will saturate. Make a rough plot of pulse height *vs*. bias; choose a bias corresponding to about 95% of saturation (or the maximum output from the bias supply) and use this for all subsequent measurements.

Connect the output of the main amplifier to the PHA input. Adjust the gains so the californium α line appears at about 60% of full scale. Once you have understood the basics, you should take some time to understand the further use of the program to analyze the data. Learn how to define a "Region of Interest" (ROI), and get the centroid, width, and area of a peak. In addition to energies, record the count rate.

You should print out pulse height spectra for this and subsequent runs and label all prominent features. Turn these in with your lab report.

ii) Use of Californium and Pulser for Calibration of Energy *vs.* Channel Number

The Californium peak will give you the PHA channel corresponding to an α with energy 6.2 MeV. Write down the channel number corresponding to your energy centroid. You now need to establish how the peak channel varies with energy. As a working hypothesis we assume the dependence is linear so we can write

$$E_\alpha = k(n - n_0)$$

where n is the channel number and the n_0 term allows for the possibility of an offset. The best way to determine n_0 is with a pulser. The pulser can also be used to establish whether the *electronics* is in fact linear. It is very difficult to prove that the solid-state detector itself has a linear response with energy; however, it is expected to be quite linear if the depletion region is sufficiently thick.

Turn off the bias voltage, let the vacuum chamber up to atmospheric pressure, and remove the α source. Connect the attenuated output of the pulser to the test input of the preamp. Choose an attenuation setting on the pulser to give a reading just above the channel number of the ^{252}Cf peak with a dial setting of 10 on the pulser. Record the peak channel for dial settings of 0.50, 1.00, 2.00, 3.00, …, 10.0. You may need to lower the Threshold to see the lowest point. Make a plot of the peak channel *vs.* dial settings. Do a fit to the data and use this to determine n_0.

You can then determine k in units of keV per channel from the position of the peak for the ^{252}Cf α's and use the equation above to convert from channel number to energy. Learn how to input the calibration into the MCA program so you can change the scale from channels to MeV.

c. Measurement of the Polonium-210 α Energy and Estimation of the Source Activity

Replace the ^{252}Cf source with a ^{210}Po button source. [The half life of ^{210}Po is quite short so try to find a source that isn't too "old".] Place the source as close as possible to the detector and make sure they are well aligned. Measure the detector–source spacing and the diameter of the detector so you can calculate the solid angle the detector subtends. Take a spectrum and obtain the number of counts in the peak and the live time. From the observed rate for the source and the detector geometry, estimate the activity of the source in units of Curies, where 1 Ci = 3.7×10^{10} decays/sec. Compare this with the expected activity calculated from the nominal activity and age of the source.

d. ^{228}Th α-particle Spectrum and the 4n Sequence

Now, we will examine the level spectrum of the excited states of the lead nucleus. You will collect a multi-peak spectrum from a sample of ^{228}Th, a relatively long-lived member of the ^{232}Th radioactive decay chain (Fig. 3). You will use your calibration from the californium "standard" to measure the energy of each line. You can relate these to the expected energies in the 4n series and observe for yourself the transmutation of the elements.

Before starting, note that the overall gain of your signal chain may drift with time. You may wish to re-establish the Cf standard and check k and n_0 before doing this part.

Replace the Po α source with a ^{228}Th α source. **Handle the source with care; it is extremely fragile!** Don't touch the foil. Pump down and record the spectrum. Make sure the 8.78 MeV peak is within the range of the PHA. (You should see 6 peaks.) Define ROI's for each peak, and get the centroid, width(FWHM), and number of counts for each peak.

e. Range and Stopping Power of Alpha Particles in Air (if a 3 week experiment)

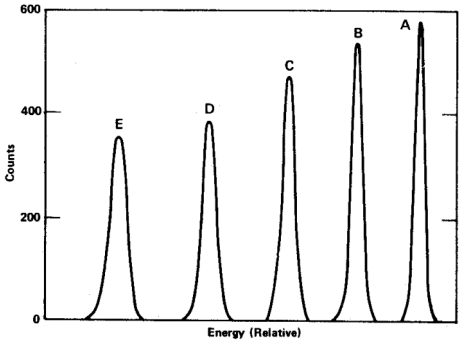
Varying the pressure in the chamber varies the effective thickness of air between the α source and the detector. By measuring the final detected α energy *vs.* pressure, you can measure the energy loss *vs.* mass thickness, your own version of the Bragg curve, and also the effective range of α's in air. This measurement, including typical data, is described in detail in Melissinos I, Sec. 5.5.3.

[NOTE: In the procedure below, the measurement is done with a polonium source. However, you would be better off with a thorium-228 source, since these sources have much higher activities. They also have the advantage that you can do several energies at once.]

Place the ^{210}Po source several centimeters from the detector and pump down the chamber. Record the spectrum. Find the centroid of the alpha peak, and verify that you are close to your calibration. Turn the bias off temporarily and bleed air into the chamber to raise the pressure by about 50 mm (of mercury). Record the spectrum. Raise the pressure while watching to counting rate and verify that all the alphas are stopped before you reach atmospheric pressure. Then pump down again and raise the pressure in 50 mm increments and record the peak positions at each point until the α peak is at too low a pulse height to observe. It is particularly important to get good data as the energy goes to zero. This is where dE/dx is largest, but changes the fastest. Also, extrapolation to the endpoint will be used to derive the range. Plot your data as you go, so you can see if you need to repeat measurements, or try for a smaller variation in pressure in this regime. Make sure you correct your pressures for the zero offset of the gauge.

At any pressure setting, the pressure will gradually tend to rise due to leaks. If you want, you can try to maintain a reasonably constant pressure as you take the spectrum by opening the pump-down valve slightly. If the pressure goes too low, bleed a bit of air into the system. This takes a bit of practice.

The density of air is $\rho \approx 0.00121\ (P/760)$ where ρ is in gm/cm^3 and P is the absolute pressure in mm. Use this to calculate the mass thickness ξ between the source and detector in units of mg/cm^2 ($\xi=\rho x$ where x is the spacing). First make a plot of the energy E_α vs. ξ. Extrapolate to $E_\alpha=0$. How does your result compare with expectations for α's in air? Note there is a thin gold layer in front of the silicon, typically 40μg/cm^2. Does this produce a significant correction to your result?



Curve	Air Thickness (mg/cm^2)	Alpha Particle Energy* (MeV)	Alpha Particle Resolution (keV)	ΔE (MeV) Measured	ΔE (MeV) Calculated
A	0.00	5.47	137	0.00	0.00
B	0.95	4.77	149	0.73	0.73
C	1.89	3.96	168	1.54	1.52
D	2.84	3.03	195	2.47	2.46
E	3.78	1.95	230	3.55	3.60

*After passing through air.

Figure 7 The Po peak walks with pressure. Work up your data as shown! (From the Ortec AN34 manual.)

Take differences ΔE between energies for successive pressure settings. Use these to estimate the rate of energy loss $\Delta E/\Delta\xi$ in MeV/(gm-cm^2) as a function of mean α energy. Plot all these $\Delta E/\Delta\xi$ data *vs.* thickness, and *vs.* α energy. Comment on any differences between your data for range and $\Delta E/\Delta\xi$ and those from Melissinos. Have you verified the basic expectation of the Bragg curve? See if your data reproduce the widening of the peak, as shown in Fig. 7.

Further Questions

(1) Using all your data, plot FWHM (or width) *vs.* $\sqrt{E_\alpha}$. Does the width increase linearly with $\sqrt{E_\alpha}$? Explain this effect in terms of the number of electron-hole pairs produced.

(2) It takes about 3 eV to produce an electron-hole pair in the silicon detector. Use this to estimate how many electrons are produced in the detector by the polonium α's. From this, estimate the ideal energy resolution if it were determined only by statistical fluctuations in the number of electrons produced. Compare this with actual resolution from your spectrum. What are some additional effects that could worsen the energy resolution?

(3) Make a good-sized diagram showing the decay chain for ^{228}Th. On it, show all α energies, lifetimes, and decay probabilities. Make a table of your α energies for ^{228}Th. Identify each with α's in the decay chain worked out above. How do the measured energies compare with those expected?

(4) Explain why the α peak has a longer tail on the low side than the high side.

(5) We make the hypothesis that the output pulse height of the detector is a linear function of α energy. Is there evidence for or against this hypothesis in your data? Explain.

(6) What is secular equilibrium? Assuming secular equilibrium for the ^{228}Th, what would you predict for the ratios of the counts in the α peaks for ^{228}Th? Compare this with the observed ratios. Is the ^{228}Th source in secular equilibrium? If not, try to explain why.

5. References

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