ABSORPTION OF GAMMA RAYS

‘Gamma rays’ is the name given to high energy electromagnetic radiation originating from nuclear energy level transitions. (Typical ranges of wavelength 0.0005 to 0.15 nm, frequency 2×10^{18} to 6×10^{20} Hz, and energy 0.01 to 2.5 MeV) The terms gamma rays, nuclear x-rays, and high-energy photons are often used interchangeably. Gamma rays traversing matter are absorbed due to a number of processes. The ability of a substance to absorb gamma rays is expressed by the linear attenuation coefficient for that substance. In this experiment an attempt will be made to verify the theoretical expression describing the absorption of gamma rays as a function of absorber thickness, and the linear attenuation coefficients and mass attenuation coefficients for lead, copper, and aluminum for gamma rays from ^{137}Cs will be measured and compared to accepted values.

Theory:

Gamma ray absorption is a random type of process; it is not possible to say whether a particular gamma ray will interact with the absorber or pass through unaffected. The processes by which gamma ray absorption occur are: 1) the photoelectric effect; 2) Compton scattering, and; 3) pair production. The photoelectric effect is described in “Determination of Planck's Constant” and Compton scattering is discussed in the self-titled experiment. Pair production is the process whereby, in the vicinity of a nucleus, a photon (gamma ray) spontaneously materialises into an electron and a positron. Pair production can only occur for gamma ray energies ≥ 1.02 MeV. In all three of these processes the gamma ray is either scattered away from the incident direction or completely absorbed. That is, if a detector is placed on the opposite side of the absorber, along the incident direction of a beam of gamma rays, only those gamma rays which did not interact with the absorber will be detected.

An expression can be derived which gives the number, N, of gamma rays that will pass through an absorber without interacting, as a function of the absorber thickness and the incident number of gamma rays. Consider a number, N_o, of gamma rays incident on an absorber of thickness x. Suppose the absorber is divided into n sections of equal thickness Δx (see Figure 1).

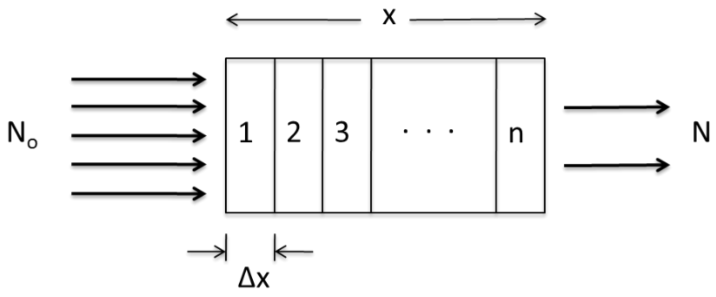


Figure 1: The absorber is divided into n section of equal thickness Δx

Since gamma ray absorption is a random process, it is reasonable to expect that the change in the number of gamma rays, ΔN, due to absorption in a section of the absorber, is proportional to the number of gamma rays incident on the absorber section and the absorber section thickness:

i.e.
$$\Delta N \propto N\,\Delta x \tag{1}$$

That is, the likelihood of a gamma ray interacting increases as the thickness of the absorber thickness increases, and increasing the number of incident gamma rays increases the number that will be absorbed. To make the relationship an equation, define μ, the linear attenuation coefficient, as the constant of proportionality. μ is a measure of the effectiveness of a given type of absorber. Also, note that ΔN is intrinsically negative since the number of gamma rays is decreasing due to absorption.

$\therefore$
$$\Delta N = -\mu N\,\Delta x \tag{2}$$

The relative change in the number of gamma rays, due to absorption, is

$$\frac{\Delta N}{N} = -\mu\Delta x \tag{3}$$

Consider the absorber to be separated into its n sections:

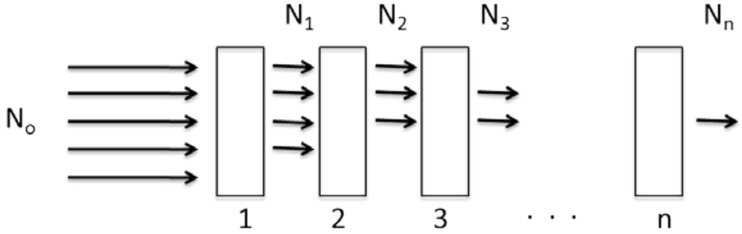


Figure 2: Gamma rays are absorbed by each section

The number of gamma rays remaining after each section of the absorber is traversed is given by:

$$N_1 = N_o - \left|\frac{\Delta N}{N}\right| N_o = N_o\left(1 - \frac{\Delta N}{N}\right) = N_o(1 - \mu\Delta x)$$

$$N_2 = N_1 - \left|\frac{\Delta N}{N}\right| N_1 = N_1(1 - \mu\Delta x) = N_o(1 - \mu\Delta x)^2$$

and $N_n = N_o(1 - \mu\Delta x)^n$ is the number remaining after passing through the complete absorber.

Now recall that $\Delta x = x/n$.

$\therefore$
$$N_n = N_o\left(1 - \frac{\mu x}{n}\right)^n \tag{4}$$

Note that the above analysis assumes that the number of gamma rays changes linearly over the width of each absorber section.

i.e. for N_1, $N_1 = N_o - N_o\mu\Delta x = c_1 + c_2\Delta x$ c_1, c_2 constants

However, the proper expression is $N_1 = N_o - N'\mu\Delta x$, where N' decreases continuously as the gamma rays pass through the absorber section. This problem can be overcome by taking smaller and smaller section thicknesses. Therefore, from equation (4):

$$N = \lim_{n\to\infty} N_n = \lim_{n\to\infty} N_o\left(1 - \frac{\mu x}{n}\right)^n = N_o e^{-\mu x} \qquad (5)$$

where N_o is the incident number of gamma rays, and N is the number transmitted through the absorber of thickness x. The above result can be obtained directly from equation (3) by integration:

$$\frac{\Delta N}{N} = -\mu\Delta x$$

$$\lim_{\Delta x\to 0} \text{implies} \frac{dN}{N} = -\mu dx$$

$$\therefore \int_{N_o}^{N} \frac{dN}{N} = -\mu\int_0^x dx$$

$$\ln N - \ln N_o = -\mu x$$

$$N = N_o e^{-\mu x}$$

That is, the number of gamma rays remaining decreases exponentially as the absorber thickness is increased. Although the desired result follows rather easily by integrating equation (3), such is not always the case. In this instance, equation (3) can be written as

$$\frac{dN}{dx} = -\mu N$$

which is an easily solved differential equation. However, for some types of problems, the differential equation may be quite complicated. In that case, it is useful to use an iterative type of solution as was done initially. Also, note that the iterative calculation lends itself rather nicely to computer programming.

There is also a relationship between an element’s atomic number Z and its mass attenuation coefficient, which is defined as the linear attenuation coefficient divided by the material’s density ρ. We expect μ/ρ to increase with Z, however this relationship is not necessarily linear.

Apparatus:
The source used in this experiment is ^{137}Cs, which emits gamma rays with an energy of 0.662 MeV. There are four lead absorber disks of thickness 1.0 mm, 1.6 mm, 3.2 mm, and 6.5 mm (each ±0.1 mm), a number of copper disks whose thicknesses can be measured, and numerous aluminum absorber plates whose thicknesses are stamped on the plate ends.

The source is collimated to provide an incident beam of gamma rays, and the detector is well-shielded and collimated to reduce background counts and to detect only those gamma rays which come directly from the source.

The detection and analysis system consists of a NaI(Tl) scintillation crystal and photomultiplier tube connected to a high voltage supply and a multichannel analyser (MCA) connected to a PC.

Gamma rays passing into the NaI(Tl) crystal cause flashes of light (scintillations) inside the crystal. These flashes of light release electrons from the photocathode of the photomultiplier tube (by the photoelectric effect). The high voltage applied to the photomultiplier tube causes the electrons to be channelled through the various stages of the tube, with amplification of the number of electrons occurring at each stage. The result is a pulse at the output of the photomultiplier tube, the voltage of the pulse being proportional to the energy deposited in the crystal by the gamma ray. After linear amplification the voltage pulse is digitized by the analogue-to-digital-converter (ADC) in the multichannel analyser, and the computer monitor displays the number of pulses versus channel number. The channel number is directly proportional to the photomultiplier tube pulse voltage and hence to deposited gamma ray energy. The monitor thus shows the energy distribution of the gamma rays being detected. A diagram and photograph of the apparatus are shown in Figure 3.

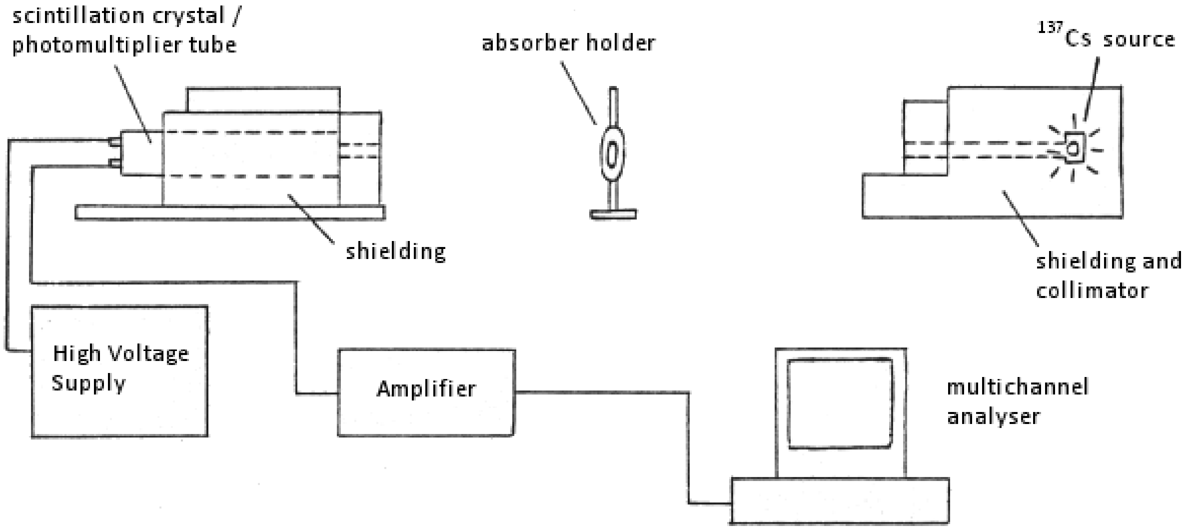
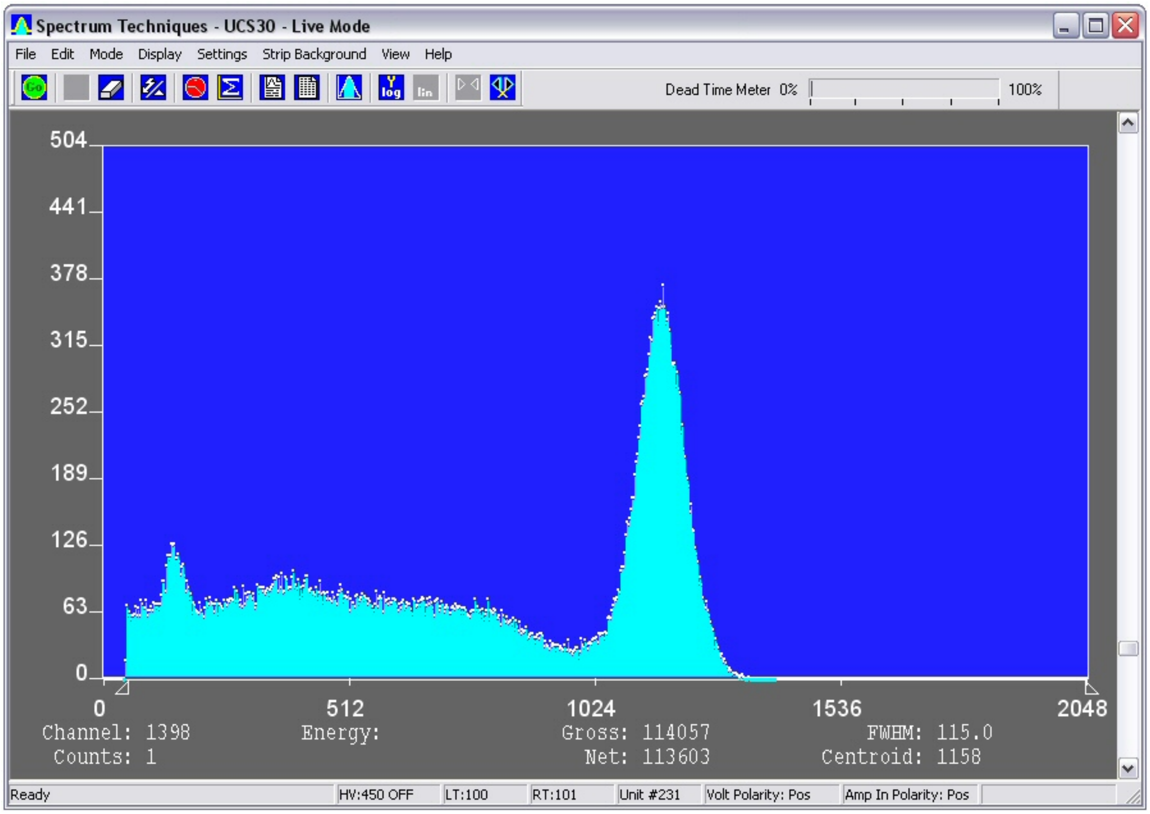


Figure 3: Schematic diagram of apparatus

Figure 4: Photograph of apparatus



Dead Time Meter 0% 100%

Channel: 1398
Counts: 1
Energy:
Gross: 114057
Net: 113603
FWHM: 115.0
Centroid: 1158

Ready | HV:450 OFF | LT:100 | RT:101 | Unit #231 | Volt Polarity: Pos | Amp In Polarity: Pos

Figure 4: A typical energy spectrum for a monoenergetic gamma source

A number of features of the spectrum are worthy of mention. The large peak results from complete gamma ray absorption whether by a single photoelectric event, or by Compton scattering followed by a photoelectric event. (Because the pulse amplitude per MeV is nearly independent of the kinetic energy imparted to the electrons for NaI(Tl), the response of the detector is linear. Thus the pulse amplitude is directly proportional to the amount of gamma ray energy deposited, no matter what the process.) Although the incident gamma ray is monoenergetic, the peak has a width due mainly to fluctuations in the number of electrons released at the photocathode per fluorescent photon.

The continuum of energies from zero to the start of the peak is due to the various amounts of gamma ray energy absorbed by the crystal for Compton scattering. (A gamma ray that interacts with the crystal via a single Compton event and then exits the crystal will not deposit all of its energy.)

The small low-energy peak is due to gamma rays that are backscattered from the source shielding or the photomultiplier window into the crystal.

Procedure and Experiment:

Familiarize yourself with the software that will be used in this experiment.
Refer to "Software UCS30-USX" handout.

NOTE: For reliable results, the electronics should be turned of half an hour before measurements are to be taken.

NOTE: In the theory section, the discussion involved the <u>number</u> of gamma rays. However, since the source emits gamma rays continuously in all directions, the terms N and N_o should have been defined as <u>numbers</u> of gamma rays <u>per unit area per unit time</u>. This will not affect the results, though, as long as counts are normalised to a constant time interval. (i.e. convert to counts per second or counts per minute, or counts in 5 minutes, etc.) The area over which measurements are made is constant because the active frontal area of the scintillation crystal does not change.

Also, recall that for a random process such as absorption of radiation, the experimental uncertainty in a count measurement N is given by $\sqrt{N}$. Thus the relative uncertainty

$$\frac{\delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

decreases as the number of counts recorded increases. Therefore, the longer the time interval over which counts are recorded, the better the experimental accuracy. For example, suppose a one minute measurement yields 100 counts and a four minute measurement yields 400 counts. Although the result in both instances is a count rate of 100 counts/min, in the first case the result is $(100 \pm \sqrt{100})/1$ min = 100 ± 10 counts/min, while in the second case it is $(400 \pm \sqrt{400})/4$ min = 100 ± 5 counts/min.

When performing a counting experiment a compromise must be reached between the amount of time available for the experiment and the desired accuracy. When choosing time intervals for the counts to be made in this experiment, be sure that all of the measurements can be made in the lab period, and remember that as the absorber thickness is increased the count rate will decrease, so longer time intervals will be required to maintain a desired degree of accuracy.

1. Log-in to the computer. The password is brianlab
2. Turn on the UCS30 device.
3. Double-click on the UCS30 or USX icon on the desktop.
4. ***Click on the Mode menu and select 'PHA (Amp In)', the 2nd item on the list***.
5. Click on the Settings menu and select Amp/HV/ADC. The high voltage should be set to **1100**. Click the button to turn it On. Check that the coarse and fine amplifier gains are **32** and **2.00** respectively, the conversion gain is **2048**, and that the Amp In Polarity is positive. (If any of these settings are different than stated above, consult the lab instructor.)
6. Allow at least five minutes for the high voltage power supply to warm up.
7. Ensure that the two large lead bricks are in front of the source. It will be assumed that these bricks absorb all radiation from the source that would otherwise strike the detector. Measure the background radiation (due to other sources in the building, cosmic rays, the earth, etc.) by counting for 600 seconds.

   Record the total number of counts obtained in all channels of the display.

   The background rate is the number of counts detected divided by 600 seconds. This background rate must be subtracted from your measurements to obtain the rate due to the source only. Once the background measurement has been completed, remove the two lead bricks. (DO NOT REMOVE ANY OF THE OTHER LEAD SHIELDING THAT SURROUNDS THE SOURCE).
8. Visually check that the absorber holder is in line with, and about midway between, the source and detector.
9. With no absorber, measure the incident gamma ray count rate. Use a time of 100 s. The spectrum (energy distribution) of gamma rays that you observe is due to characteristics of the detector system. The incident gamma rays are monoenergetic at 0.662 MeV. As well as measuring the gamma count rate as described above, record the channel number of the gamma energy peak.
10. Carefully measure the thicknesses of the 4 available lead absorber disks. Take an average of 5 readings for each disk, as the soft metal has been distorted by previous students. Be gentle and try not to further distort the disks.
11. Measure the gamma ray count rate and peak channel number for all possible combinations (15) of the four lead absorber disks. **Remember to set and record the count time**, and to increase the count time as the absorber thickness is increased.
12. Measure the gamma ray count rate and peak channel number for various thicknesses of copper absorber plates. (BE SURE TO RECORD THE THICKNESS OF EACH PLATE AS IT IS USED.)
13. Measure the gamma ray count rate and peak channel number for the aluminum plate absorbers. Use the available C clamp to ensure that the plates are mounted vertically (perpendicular to the incident gamma rays). Since aluminum is not as effective an absorber

as lead, and since most of the plates are approximately the same thickness, take measurements for no plate, one plate, two plates, etc. until all the aluminum plates are between the source and detector. (BE SURE TO RECORD THE THICKNESS OF EACH PLATE AS IT IS USED.)

Analysis

Analysis Goals:

1. Find the linear attenuation coefficient for each material by plotting the data as instructed below and finding the slope of the line.
2. Find the mass attenuation coefficient for each material by dividing the linear attenuation coefficients by the density of the respective materials, which can be found online.
3. Compare linear and mass attenuation coefficients to accepted values and comment on how the mass attenuation coefficient is related to each element's atomic number, Z.

For each set of results (lead, copper, and aluminum) plot the natural logarithm of the gamma ray count rate (corrected for background) versus absorber thickness.

i.e. Plot *ln N* versus *x*. According to theory, since

$$N = N_o e^{-\mu x}$$

$$\therefore \qquad ln\ N = ln\ N_o - \mu x$$

Since N_o and μ are constants, the theoretical prediction is that *ln N* versus *x* is linear with a slope of $-\mu$.

Do your results verify the theoretical relationship between count rate of transmitted gamma rays and absorber thickness?

Determine the experimental values of the linear attenuation coefficients for lead, copper, and aluminum for gamma rays from ^{137}Cs. How do your values compare with the accepted values of 1.21 cm^{-1}, 0.652 cm^{-1}, and 0.202 cm^{-1} respectively?

Determine the experimental values of the mass attenuation coefficients for lead, copper, and aluminum by dividing μ by the density ρ. How do your values compare with the accepted values of 0.107 cm^2/g, 0.073 cm^2/g, and 0.075 cm^2/g, respectively? Describe the relationships between the materials' atomic numbers Z and their mass attenuation coefficients.

In your report discuss any sources of error which may be inherent in the design of the experiment. (HINT: Consider the geometry of the apparatus and the processes by which gamma rays interact with matter.) What assumptions were made in the theory? Do these assumptions hold for the actual experiment? Would you expect your μ values to be higher or lower than the accepted values? Explain.)

Which absorber type is more effective: lead, copper, or aluminum? Try to think of a few reasons to explain why.

How does the energy (peak channel number) of the transmitted gamma rays vary with absorber thickness? Discuss.