

Gamma Ray Spectroscopy

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1 Objectives

1. To acquaint the students with some of the basic techniques used for measuring gamma rays.
2. To gain experience in the energy calibration and interpretation of gamma ray spectra for the purpose of identifying gamma ray emitting isotopes.

2 Equipment Needed for the Experiment

1. ^{60}Co radioactive source (PASCO).
2. NaI(Tl) scintillation detector with photomultiplier tube (REXON Components Inc.).
3. UCS30 Universal Computer Spectrometer (SPEC TECH).
4. Position stand with sample tray and lead shield.
5. BNC-6 Signal Cable (Advanced Digital Cables, Inc.), and MHV-6 High voltage cable (CAROL).

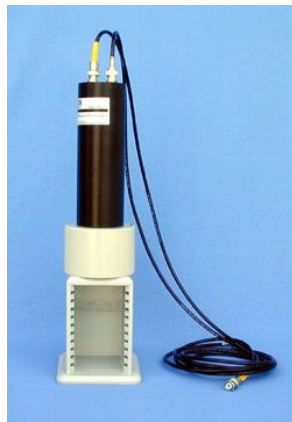


Figure 1: SDA-38 Scintillation detector, with position stand, lead shield and cables.

3 Introduction

3.1 Gamma ray detection

In this experiment you will study the radioactive decay of a nucleus by detecting gamma ray emissions. Gamma ray detection is a complicated, multi-step process: the gamma ray enters a NaI(Tl) scintillator crystal where it produces a rapidly moving free electron that, in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways, one of them being the emission of visible light (fluorescence). Thus a single high energy

gamma ray entering the scintillator produces a flash of low energy photons. These photons are directed to the photosensitive surface of a photomultiplier tube, where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier tube and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube. Consequently, the voltage pulse is proportional to the initial energy of the fast electron.

3.2 Multi-Channel analysis

When a radioactive source is placed near the scintillator, the photomultiplier produces a series of pulses, each corresponding to the decay of a single nucleus. The amplitude of each pulse is related to the energy of the electron freed by the gamma ray. These pulses are studied using either a single- or multi-channel analyzer. A single channel analyzer (SCA) counts the number of voltage pulses whose height falls within a given (adjustable) window of values, while a multi-channel analyzer (MCA) sorts the pulses according to height and the counts the number in each window to give a spectral (energy) distribution of the fast electrons. Figure 2 shows a typical MCA spectrum. In order to relate this spectrum to the nuclear decay, we need to understand how gamma rays interact with matter.

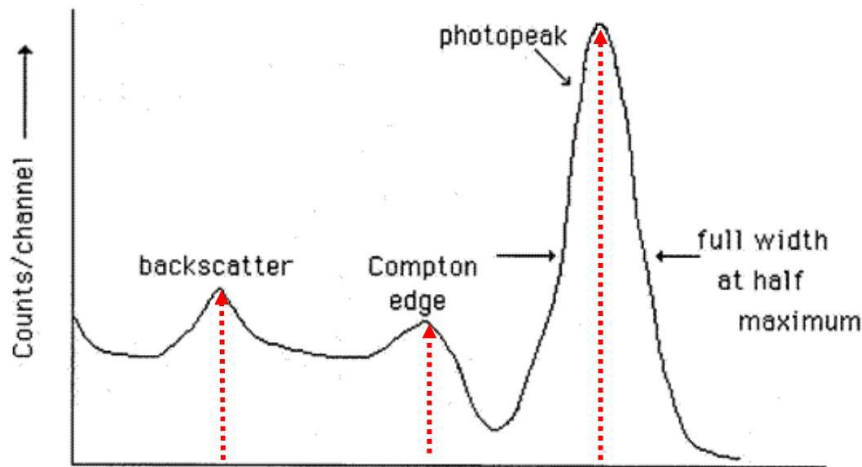


Figure 2: NaI(Tl) energy spectrum for ^{137}Cs

3.3 Interaction mechanisms for gamma rays with matter

When entering a crystal, gamma rays produce fast charged electrons by three different processes: the photoelectric effect, the Compton effect (Compton scattering) and pair production. It is these fast electrons, which give rise to scintillations, not the gamma ray. The observed spectral distribution will thus depend on the detailed interaction process of the gamma rays in the crystal.

Consider a beam of mono-energetic gamma rays striking the scintillator. For our purposes the most important energy loss mechanism is the photoelectric effect. When a gamma ray strikes an ion in the crystal, it is absorbed and all of its energy is

transferred to one of the bound electrons, which is freed and moves rapidly through the crystal. Since the energy of the gamma ray (typically about 0.5 MeV) is much greater than the binding energy of the electron of the ion (typically 10 to 100 eV), the energy of the freed electron can be considered equal to that of the incoming gamma. The energy lost in 'freeing' the bound electron is too small to be detected in the overall energy of the of the electron especially since the energy resolution of the detector is only about 10% (This means that for any energy E_o , on the spectrum, the uncertainties are $E_o \pm 0.1E_o$). Thus the photoelectric effect results in a peak, called the photopeak, in the photomultiplier spectrum at an energy equal to that of the incoming gamma ray.

In Compton scattering, the gamma ray is not absorbed, rather scattered through an angle θ by an electron, which recoils and carries away some of the gamma ray's energy E . The scattered gamma ray then escapes from the scintillator; the probability that a gamma ray Compton scatters in a typical size scintillator is quite small (1% to 10%), which means you are unlikely to detect a gamma ray that has undergone two Compton scatterings. The gamma ray's initial wavelength is $\lambda = hc/E = 1240/E$ nm, where E is in eV. The change in wavelength is:

$$\Delta\lambda = \frac{h}{mc}(1 - \cos\theta) = 0.00243(1 - \cos\theta) \text{ nm}, \quad (1)$$

where h is Planck's constant, m is the mass of the electron and c is the speed of light. The energy of the scattered photon is given by:

$$E' = \frac{E}{1 + \frac{E}{mc^2}(1 - \cos\theta)} \quad (2)$$

From these equations you can see that the energy of the scattered electron is then given by:

$$E_e = E' - E \quad (3)$$

This is also equal to the energy loss of the original gamma ray photon, will vary from zero (when $\theta = 0^\circ$) to a maximum corresponding to a wavelength shift of 0.00486 nm (when $\theta = 180^\circ$). The maximum energy transferred by the photon to the electron through Compton scattering is called the Compton edge. The energy distribution of Compton scattered electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost flat plateau from zero energy up to the Compton edge where it drops off sharply (at a rate limited by the energy resolution of the tube).

The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator. In this case the

observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. For ^{137}Cs the Compton scattered gamma rays will have energies ranging from 181 KeV up to the full 622 KeV. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ . But $\cos\theta$ varies only slowly with θ for θ near 180° , which means that these gamma rays will all have energies near 181 KeV. So photons which will be scattered at 180° by a plate kept behind the source will all roughly correspond to the same energy. This energy for the case of Co-60 will be around 0.2 MeV. The resulting energy peak is then called the backscatter peak. It can be enhanced by placing a sheet of lead around the outside of the scintillator.

The third interaction mechanism is pair production. If the incoming gamma ray energy is above $1.02\text{MeV} = 2mc^2$, the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy E . (Of course, either might escape the crystal after partial loss of kinetic energy.)

But the spectrum is actually more complicated since if the positron has been slowed down and stopped in the crystal, it will annihilate with an electron and emitted two gamma rays, each of energy mc^2 . One or both of these gamma rays may be absorbed in the crystal, and thus contribute to the height of the photomultiplier output pulse. Pair production therefore produces a “full energy” peak (E), a “one-escape peak” ($E - mc^2$) and “two escape peak” ($E - 2mc^2$), depending upon whether both annihilation photons are absorbed in the scintillator or one, or both, escapes.

All of these 3 processes are shown in Figure 3. The final question to consider is that of the relative importance of the three interaction mechanisms, which depend in different ways upon the energy of the gamma ray. For low energy rays, the photoelectric effect predominates. Since the photopeak directly yields the energy of the gamma ray, most scintillators are designed to maximize the photopeak. In the NaI(Tl) scintillator you will use, a small amount of the heavy metal thallium is added for this purpose when the crystal is grown. (The strength of the photoelectric effect depends strongly on the number of electrons bound to the ion.) As E increases, the photoelectric absorption decreases rapidly, while the Compton scattering decreases much more slowly and predominates above several hundred KeV. The absorption coefficient for pair production rises rapidly above the threshold $E = 1.02$ MeV and exceeds the Compton scattering, while photoelectric absorption becomes negligible.

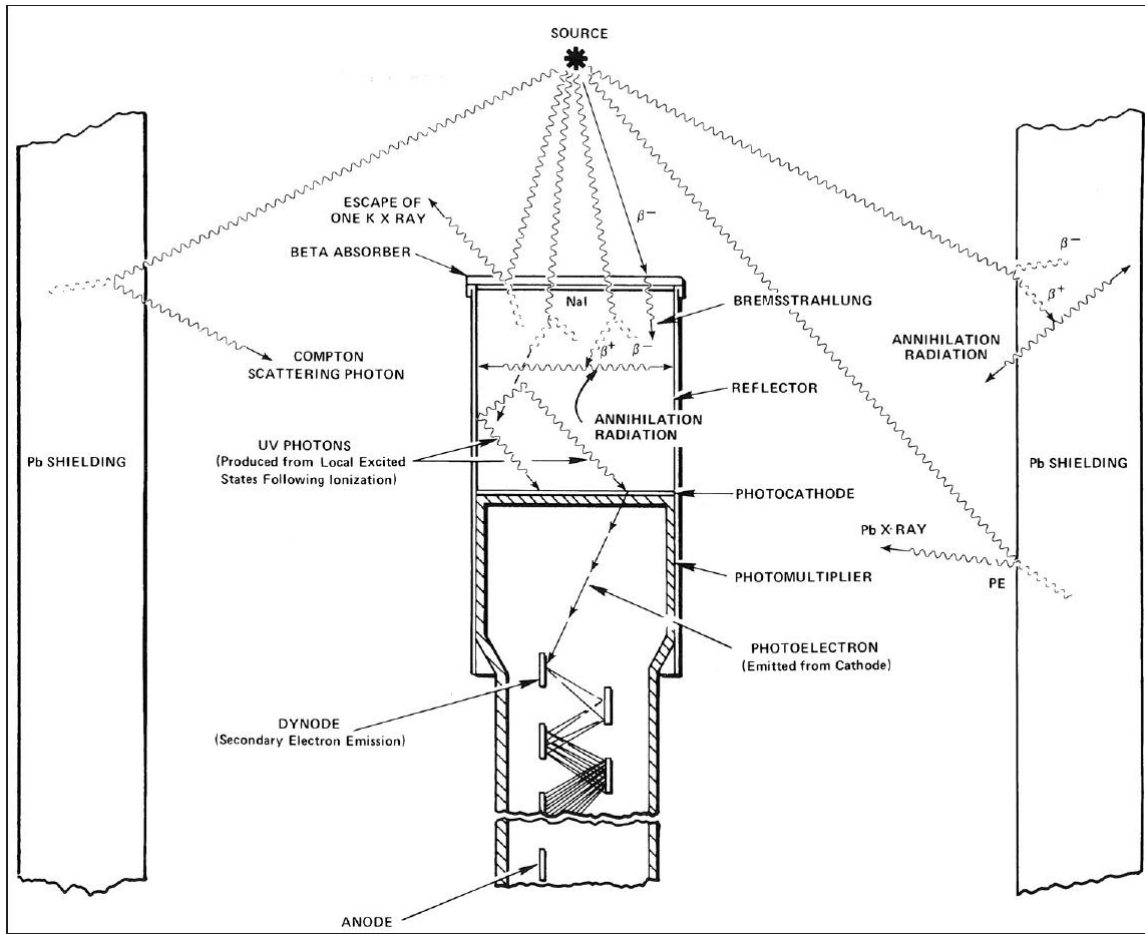


Figure 3: The Structure of the NaI(Tl) Detector and Various Types of gamma-ray interactions that occur in the typical source-detector-shield configuration.[1]

4 The NaI(Tl) Detector

The structure of the NaI(Tl) detector is illustrated in Figure 3. It consists of a single crystal of thallium activated sodium iodide optically coupled to the photocathode of a photomultiplier tube. When a gamma ray enters the detector, it interacts by causing ionization of the sodium iodide. This creates excited states in the crystal that decay by emitting visible light photons. This emission is called a scintillation, which is why this type of sensor is known as a scintillation detector. The thallium doping of the crystal is critical for shifting the wavelength of the light photons into the sensitive range of the photocathode. Fortunately, the number of visible-light photons is proportional to the energy deposited in the crystal by the gamma ray. Surrounding the scintillation crystal is a thin aluminum enclosure, with a glass window at the interface with the photocathode, to provide a hermetic seal that protects the hygroscopic NaI against moisture absorption. The inside of the aluminum is lined with a coating that reflects light to improve the fraction of the light that reaches the photocathode.

Most isotopes used for gamma-ray measurements also have beta-emissions in their decay schemes. The beta particles will usually be absorbed in the surrounding material and not enter the scintillation detector. For this experiment, the beta emissions cause negligible interference. Most of the betas are absorbed by the aluminum shield encapsulating the detector. The gammas, however, are quite penetrating, and will

easily pass through the aluminum shield.

At the photocathode, the scintillation photons release electrons via the photoelectric effect. The number of photoelectrons produced is proportional to the number of scintillation photons, which, in turn, is proportional to the energy deposited in the crystal by the gamma ray.

The remainder of the photomultiplier tube consists of a series of dynodes enclosed in the evacuated glass tube. Each dynode is biased to a higher voltage than the preceding dynode by a high voltage supply and resistive biasing ladder in the photomultiplier tube base. Because the first dynode is biased at a considerably more positive voltage than the photocathode, the photoelectrons are accelerated to the first dynode. As each electron strikes the first dynode the electron has acquired sufficient kinetic energy to knock out 2 to 5 secondary electrons. Thus, the dynode multiplies the number of electrons in the pulse of charge. The secondary electrons from each dynode are attracted to the next dynode by the more positive voltage on the next dynode. This multiplication process is repeated at each dynode, until the output of the last dynode is collected at the anode. By the time the avalanche of charge arrives at the anode, the number of electrons has been multiplied by a factor ranging from 10^4 to 10^6 , with higher applied voltages yielding larger multiplication factors. For the selected bias voltage, the charge arriving at the anode is proportional to the energy deposited by the gamma ray in the scintillator.

5 Spectrometer

Figure 4 shows the block diagram of the spectrometer system. The preamplifier collects the charge from the anode on a capacitor, turning the charge into a voltage pulse. Subsequently, it transmits the voltage pulse to the supporting amplifier. At the output of the preamplifier and at the output of the linear amplifier, the pulse height is proportional to the energy deposited in the scintillator by the detected gamma ray.

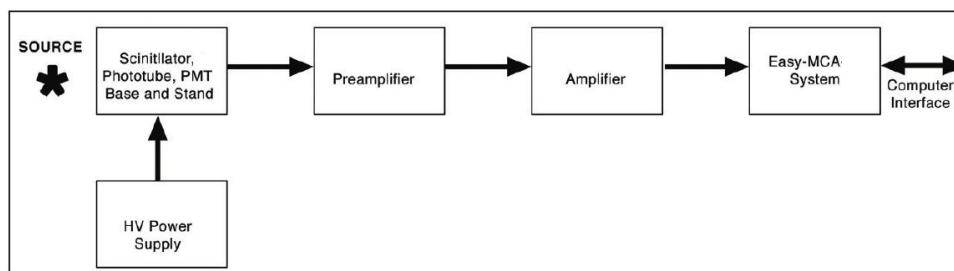


Figure 4: Electronics block diagram of gamma-ray spectroscopy system with NaI(Tl) detector.

6 The Multichannel Pulse-Height Analyzer

The Multichannel Analyzer (MCA) measures the pulse heights delivered by the amplifier, and sorts them into a histogram to record the energy spectrum produced by

the NaI(Tl) detector. The MCA is a device which takes only positive square pulses and distinguishes and counts them according to their amplitude (voltage). It contains channels and each channel corresponds to a specific voltage. Whenever the MCA receives a pulse of a specific amplitude it makes a count of that pulse on the corresponding amplitude channel. So each channel tells us that how many pulses the MCA received of that particular amplitude. The MCA being used in this experiment has a maximum of 4096 channels. The larger the number of channels the higher the energy resolution.

7 Energy Resolution

For the detectors which are designed to measure the energy of the incident radiations, the most important factor is the energy resolution. This is the extent to which the detector can distinguish two close lying energies. In general, the resolution can be measured by sending a mono-energetic beam of radiation into the detector and observing the resulting spectrum. Ideally, of course, we would like to see a delta-function like peak whose width is determined only by the natural variation in the gamma-ray energy. In reality, this is never the case and one observes a peak structure with a broader peak usually Gaussian in shape. This width arises because of fluctuations in the number of ionizations and excitations produced. The resolution is usually given in terms of the full width at half maximum of the peak (FWHM). Energies which are close than this interval are usually considered un-resolvable. This is illustrated in Figure 5. If we denote this width as ΔE , then the resolution at the energy E is given by $\Delta E/E$.

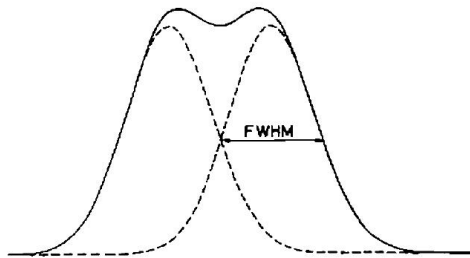


Figure 5: Definition of energy resolution. Two peaks are generally considered to be resolved if they are separated by a distance greater than their full widths at half maximum (FWHM). The solid line shows the sum of two identical Gaussian peaks separated by just this amount.

In this experiment we need to develop the energy spectrum of background radiation and then calculate the mass-absorption coefficient of lead using lead plates and a Cobalt-60 source. However first before running our spectrometer we need calibrate it first using a radioactive source with a known energy spectrum i.e the Cobalt-60 source. Therefore first we will calibrate the source and then we will work on the experiment tasks.

8 Energy Calibration Using ^{60}Co Source

Figure 6 shows the two peaks from a ^{60}Co radioisotope. Most of the time ($> 99\%$), the decay occurs by a beta emission to the 2.507 MeV excited state of ^{60}Ni . Subsequent decay to the ground state always occurs by a 1.174 MeV gamma-ray emission to the 1.3325 MeV level, followed almost simultaneously by the 1.3325 MeV gamma emission to the ground state. This means that for a Cobalt-60 source we would get 2 photopeaks in our spectrum: one at 1.174 MeV and the other at 1.3325 MeV [1].

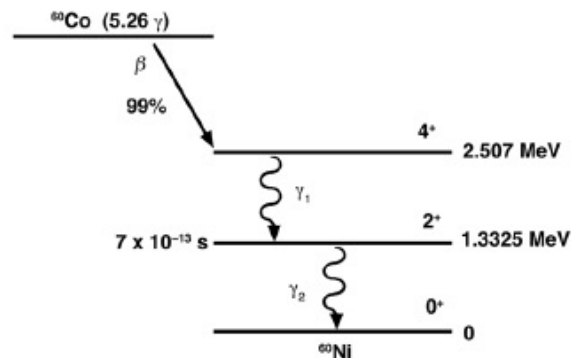


Figure 6: The decay scheme of ^{60}Co [1].

Open the ‘USX USB’ software located on your computer desktop screen. This opens the interface with which you will be working to get your required energy spectrum using the UCS 30 unit.

The interface is shown in Figure 7. First insert radioactive source of ^{60}Co on the second rack of the grey shelf on its transparent tray as shown in Figure 8.

IMPORTANT: Handle the radioactive source with caution. A large amount of exposure to radioactive sources can be harmful to health. Preferably using tongs to deal with sources. Now insert a lead and an aluminum sheet on the third rack below the source.

IMPORTANT: Do not touch the lead plates with your hands. Use rubber gloves or tongs to handle them. Touching the lead can cause the lead to be absorbed in your skin which can cause lead poisoning. These two metal sheets help increase the amplitude of the backscatter peak which makes it more distinguishable on the energy spectrum. Photons with large scattering angles $\theta \simeq 180^\circ$ are scattered back towards the detector by the lead plates kept beneath the source. The larger the number of plates the higher the backscattering rate.

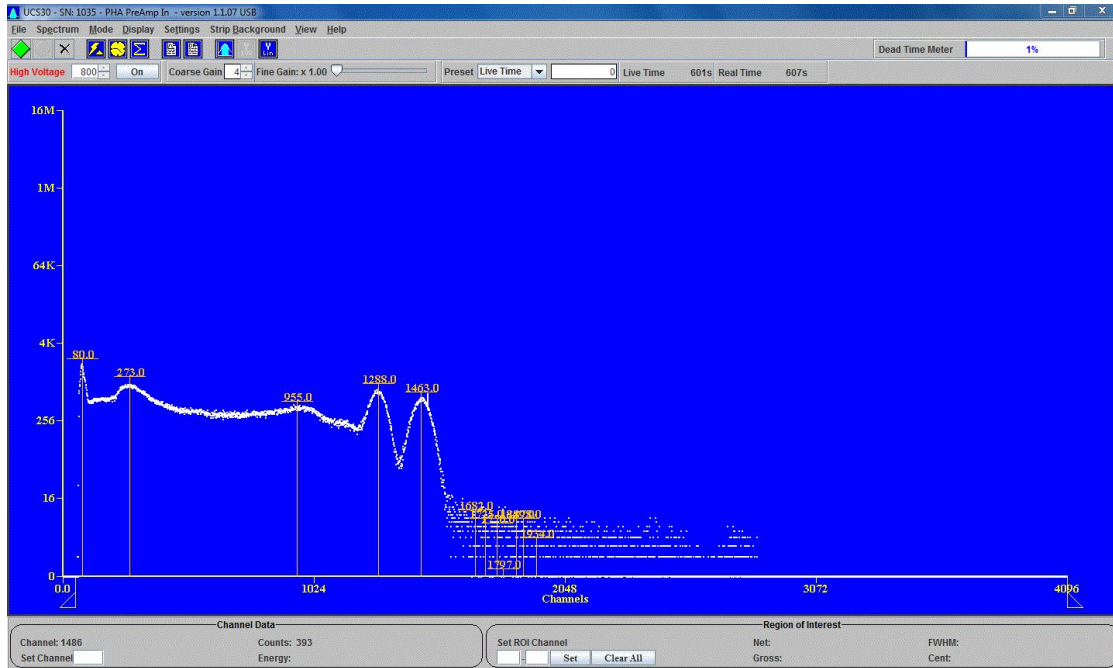


Figure 7: An uncalibrated Cobalt-60 spectrum for a voltage of 800 V and for a coarse gain value of 4.

Now go to the interface click on ‘**Settings**’ and then click on ‘**High Voltage/AMP/ADC**’. This will open a panel bar from where you can adjust the various experimental parameters. Set the voltage to 750 V, Coarse gain to 8, Fine gain to 1 and Conversion Gain or the number of MCA channels to 4096. Set the low discriminator level to 60 and upper discriminator level to 4096. Set the voltage to ‘**ON**’ and click ‘**OK**’.

This interface will now start building the energy spectrum. The y -axis shows the number counts or pulses received on a particular channel by the MCA and the scale is logarithmic. The x -axis shows the respective channels on the MCA. Let the spectrum build for a period of 500 seconds. The spectrum will look like as shown in Figure 7. Click on ‘**View**’ and then click on ‘**Peak Finder**’. This will show you all the channel numbers of the various peaks that would be visible on the spectrum.

Now to carry out your energy calibration right click with your mouse on the spectrum and then go to ‘**2-point calibration**’ in ‘**Energy calibration**’. The software will first ask you the units you want to convert your x -axis into. For this case they would be converted to ‘**MeV**’ from ‘**channels**’. After this the software will ask you the respective peak channel number and the energy you want to assign it. Like for example in this case in Figure 7 the two peaks are at channel numbers 1288 and 1463. So you will assign the first energy of 1.174 MeV to the peak at channel number 1288 and to the other higher channel number of 1463 you will assign 1.3325 MeV. Then click on ‘**OK**’ and the software will automatically calibrate the rest of the x -axis to energy units in MeV. The new calibrated spectrum will now look something like 9.

The Compton edge peak and the backscatter peak will also be noticeable with their respective energies now at 0.24 MeV and 0.86 MeV. The energy of the Compton edge peak on the spectrum should correspond to the value of energy from Equation (2) for the case of $\theta = 0$. And for the case of $\theta = 180^\circ$ the energy should correspond to the backscatter peak energy visible on the spectrum on Figure 9. In this equation



Figure 8: The source is kept on its tray on the second rack in the shelf. The lead sheet for enhanced backscattering is kept on an aluminum sheet which is kept on the third rack in the shelf.

	E'_{180°	$E_e max$
1.17 MeV		
1.33 MeV		

Table 1: Energy values calculated from 2.

$mc^2 = 0.511$ MeV which is the rest mass energy of the electron.

Exercise Now you need to check your calibration by calculating values for the Backscatter and the Compton Edge peaks. You will calculate their values theoretically using equations (2) and (3) and then compare them with your experimental values obtained from the spectrum. First calculate the value of E' for the case $\theta = 180^\circ$ to calculate the energy of the Backscatter peak and then subtract the E'_{180} value from E to obtain the value for the Compton Edge peak ($E_e max$). Calculate these two values of E'_{180} and $E_e max$ first for $E = 1.17$ MeV and then for $E = 1.33$ MeV and then take the average of both. Fill in your values in the following table:

Calculate the average for the two E'_{180° values and for the two $E_e max$ values. Now compare these two averaged-out energy values with two experimental values of Compton and Backscatter peaks you got from the calibrated energy ^{60}Co . How do they compare? What does this tell you about the accuracy of your calibration?

Save your calibrated spectrum as a '**Spectrum file**'. To save your data in the form of columns of energy and counts save your spectrum as a '**Tab Separated file**'. And

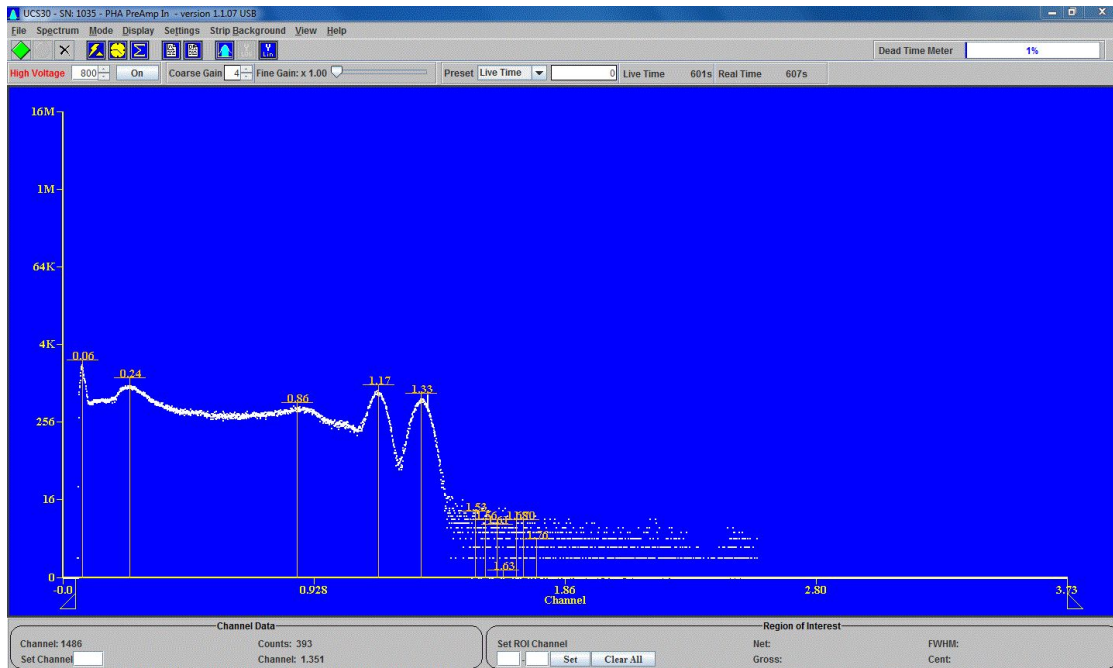


Figure 9: A calibrated Cobalt-60 spectrum for a voltage of 800 V and for a coarse gain value of 4.

to save your setup settings also save a 'Setup file' of your spectrum.

8.1 The background radiation energy spectrum

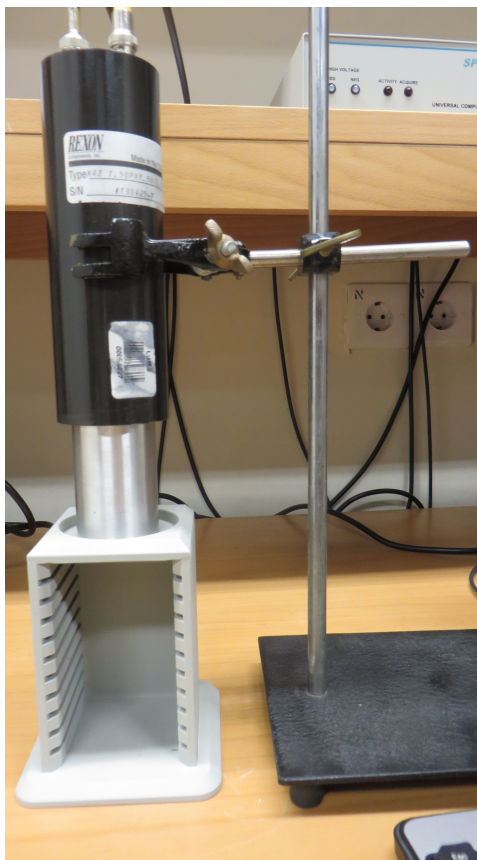


Figure 10: The detector setup for taking an experiment run for background radiation.

Exercise After you have saved your data for the calibrated energy spectrum of Cobalt, clear the spectrum by clicking on the cross located at the top left corner of the UCS interface. Now setup the detector as shown in Figure 10.

Now as the calibration has been performed we can now work towards obtaining a background radiation energy spectrum. The settings for that will be the same as for the Cobalt-60 run. On the same voltage, coarse gain and calibration settings you will now take an energy spectrum of background radiation. As compared to the activity rate of Cobalt, the background radiation activity is considerably lower so this experiment will be run for a period of 2 days. This will allow you to gain a considerable amount of data for analysis. The lower discriminator level will be set at 0.15 MeV and the upper level will be set at 3 MeV. The background radiation energy spectrum that you obtain would look like the spectrum shown in Figure 11.

With the aid of the '**Peak Finder**' and using Figure 12 try to determine out the sources and the energies of the various peaks that you have obtained on your spectrum. Fill in your values using a format similar to the one used in Table 2. Calculate the percentage errors in all your energy values (Percentage error = $\frac{\text{Energy difference}}{\text{Observed Energy}}$). What do these values tell you about the accuracy of your calibration using the Cobalt-60 source?

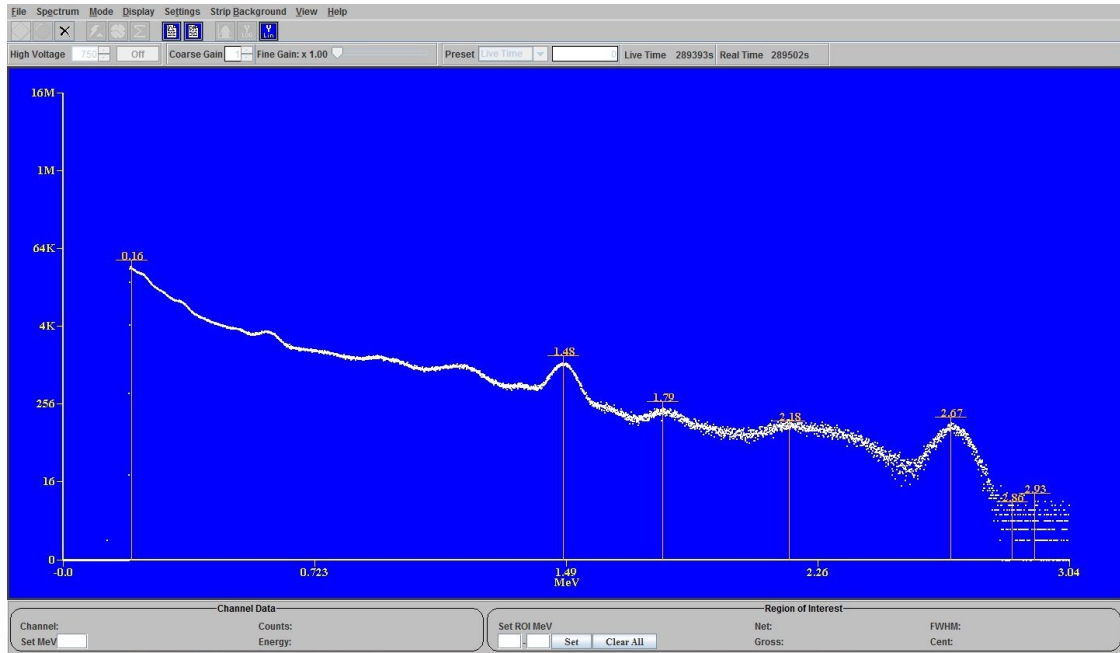


Figure 11: A calibrated energy spectrum of background radiation taken at 750 V and a coarse gain value of 8 built over a time interval of around 80 hrs.

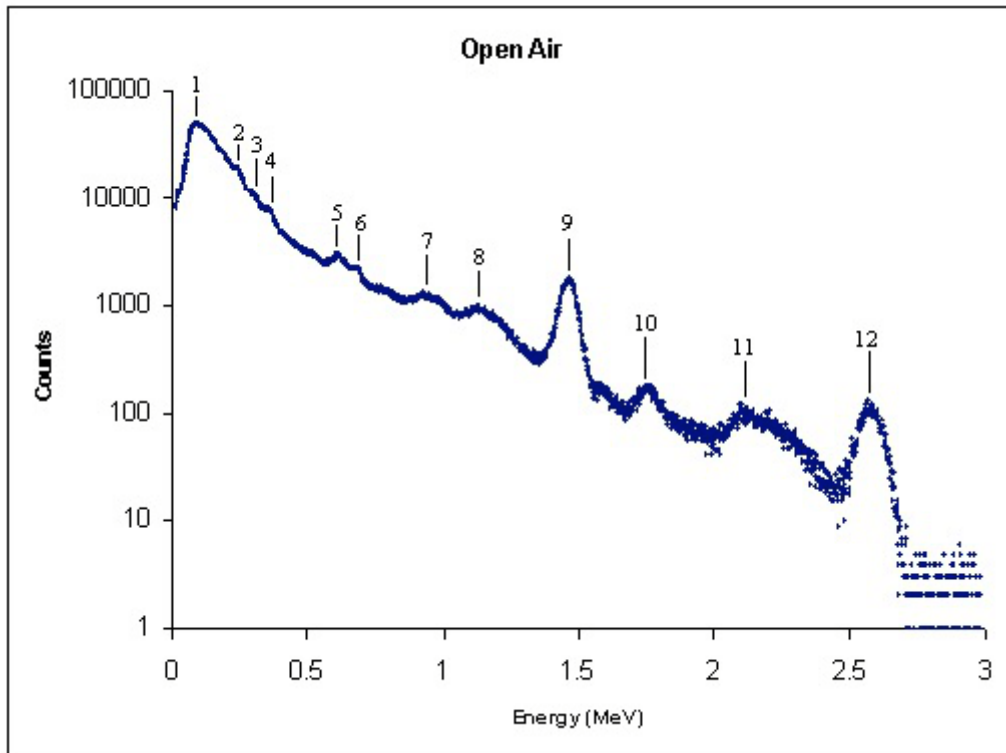


Figure 12: A calibrated energy spectrum of background radiation showing the various peaks obtained from background. The respective energies and radioactive sources of these peaks are shown in Table 2 [3].

9 Mass Absorption Coefficient

The purpose of this experiment is to measure the mass absorption coefficient for 1.17 MeV and 1.33 MeV gamma rays in lead.

Peak	1	2	3	4	5	6
Channel no.						
Known Energy (MeV)	0.094816	0.239816	0.300716	0.357266	0.605216	0.670466
Source		214 Pb	214 Pb	214 Pb	214 Bi	137 Cs
Observed Energy (MeV)						
Difference						
Percentage Error						

Peak	7	8	9	10	11	12
Channel no.						
Known Energy (MeV)	0.935816	1.131566	1.459266	1.750716	2.117566	2.572866
Source	214 Bi	214 Bi	40 K	214 Bi	214 Bi	208 Tl
Observed Energy (MeV)						
Difference						
Percentage Error						

Table 2: Fill in your energy values obtained from the spectrum.

The total-mass absorption coefficient can be easily measured with a gamma-ray spectrometer. In this experiment we will measure the number of gamma-ray photons that are removed from the photopeak by photoelectric or Compton interactions that occur in a lead absorber placed between the source and the detector.

From Lambert's law the decrease of intensity of radiation as it passes through an absorber is given by

$$I = I_0 e^{-\mu x} \quad (4)$$

where

I = intensity after the absorber,

I_0 = intensity before the absorber,

μ = total-mass absorption coefficient in cm^2/g ,

x = density thickness in g/cm^2 . This is the product of the density in g/cm^3 times the thickness in cm.

To obtain the absorption coefficient, it is convenient to plot the following quantity and fit with a straight line:

$$\ln \frac{I}{I_0} = -\mu x \quad (5)$$

The number of counts N will be a measure of the intensity so $N/N_0 = I/I_0$. Therefore we will be measuring the decrease in the net counts of the 1.33 MeV peak, for each

lead sheet that will be added between the source and the detector. Here N_0 here is the number of counts obtained for a peak without any attenuation.

To calculate the number of pulses or counts we get for a peak we simply have to select an ROI (Region of Interest) around the peak. Selecting an ROI around a peak on the software spectrum automatically tells us the net counts in that ROI and also the FWHM of the peak. This can be seen in Figure 13. Finding the intensity is tantamount to finding the area under the peak.

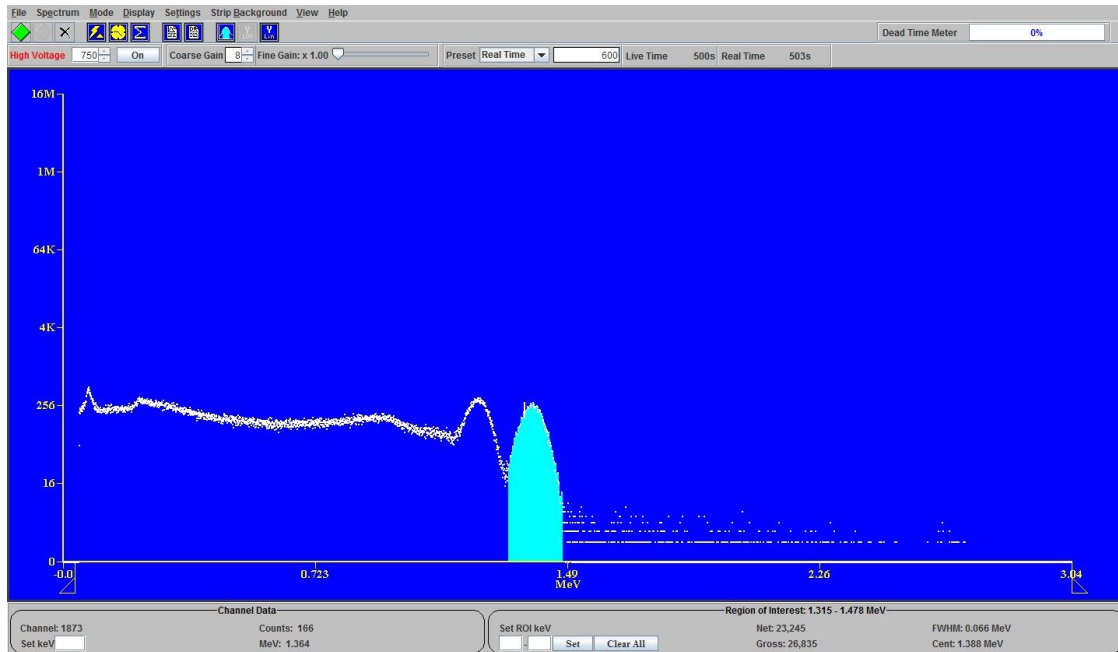


Figure 13: A calibrated energy spectrum of Cobalt-60 taken at 750 V and at a coarse gain of 8. An ROI has been defined from 1.315 MeV to 1.478 MeV. The net counts are visible on the bottom right corner of the software interface. No lead sheets have been kept between the source and the detector.

As you might have noticed there are two numbers given in the bottom right corner one is the number of net counts and the other is the number of gross counts. Gross counts is the total number of counts that the detector gets for a particular ROI in the spectrum and the net counts is the same thing minus the background radiation counts. The difference is not that much in our case but still we will be using the net counts for each of our readings.

NOTE: The voltage will be kept 750 V and coarse gain will be kept at 8. The lower value of discriminator will be kept at 0 MeV and the upper value of discriminator will be kept at 3 MeV. This time the source will be kept in the third rack on the shelf which is essentially 3 cm from the. The lead sheets will be kept on the source tray. The setup can be seen in Figure 14. First measure N_0 by just keeping the ^{60}Co source on the third rack without any lead sheets. Then start adding lead sheets one by one. The time intervals for all runs are to be kept constant at 400 s. For each lead sheet added, record your value of N after the experimental run has ended. The ROI limits will be kept constant for each reading so that no discrepancies arise.

Define your ROI by defining its limits in the lower bottom right corner or by holding on to the left mouse button and dragging it across the channels which you want to

include in your ROI.



Figure 14: The source has been kept on its tray in the third rack. Three lead plates placed on the source for attenuation of gamma rays are also visible.

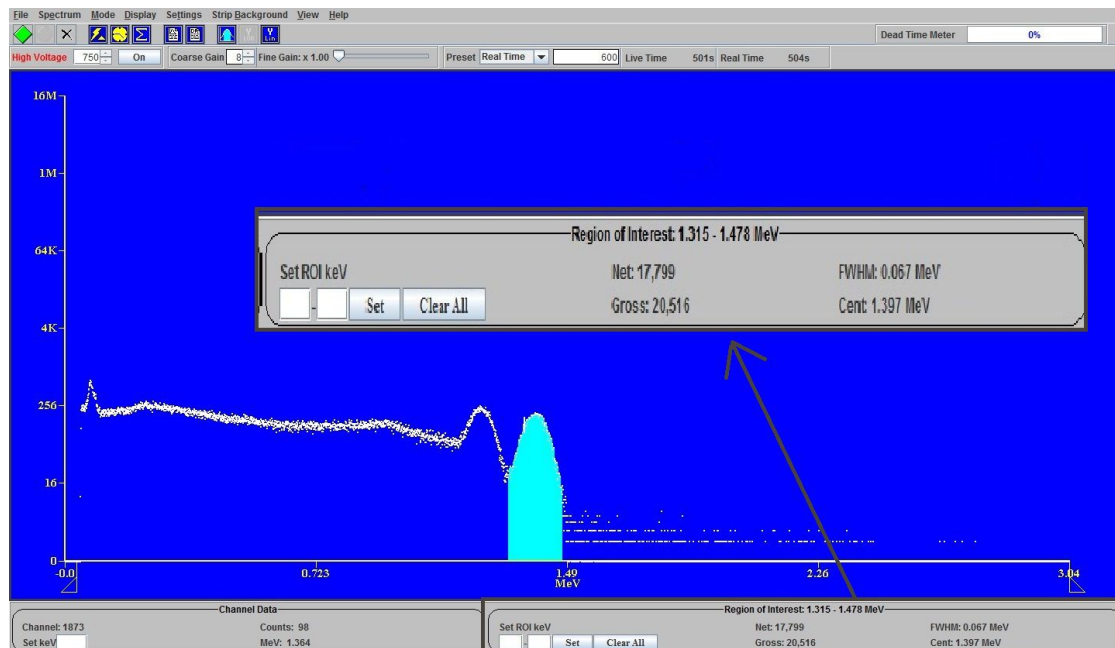


Figure 15: A calibrated and attenuated energy spectrum of Cobalt-60 taken at 750 V and at a coarse gain of 8. An ROI has been defined from 1.315 MeV to 1.478 MeV. Three lead sheets have been placed on the source. The decrease in net counts as compared to Figure 13 is quite obvious.

Measure the thickness of each lead several times ($d_1, d_2, d_3, d_4 \dots$) using a micrometer. Record your readings using the tables given below. There are 7 lead plates in total.

The uncertainties are $\sigma_{mean} = \sqrt{l.c^2 + \sigma_{data}^2}$, where σ_{data} is the standard error in the data points d_1, d_2, d_3 and d_4 and $l.c$ is the least count of the micrometer. For any value of N the uncertainty will be given by \sqrt{N} as the variable N follows a Poisson distribution.

S.no	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_{mean} (mm)	σ_{data} (mm)	σ_{mean} (mm)

$A = N/N_0$	σ_A	$Y = \ln A$	σ_Y	Pb sheets	T=Total thickness (cm)	σ_T	x (g/cm ²)	σ_x

Plot the data points of Y against data points of x in MATLAB with their respective errorbars and fit it with a straight line in MATLAB using the `lsqcurvefit` function. Look up the 'errorbar' function in MATLAB. Find the attenuation coefficient μ . The density of lead is 11.34 g/cm³ [Wikipedia].

From the NIST data [2] given in Appendix, one can see that the mass absorption coefficient for $E=1.33$ MeV is 0.056 cm²/g, and for $E=1.17$ MeV it is 0.062 cm²/g. Our μ will be somewhere between these two values. A sample plot is shown by Figure 16.

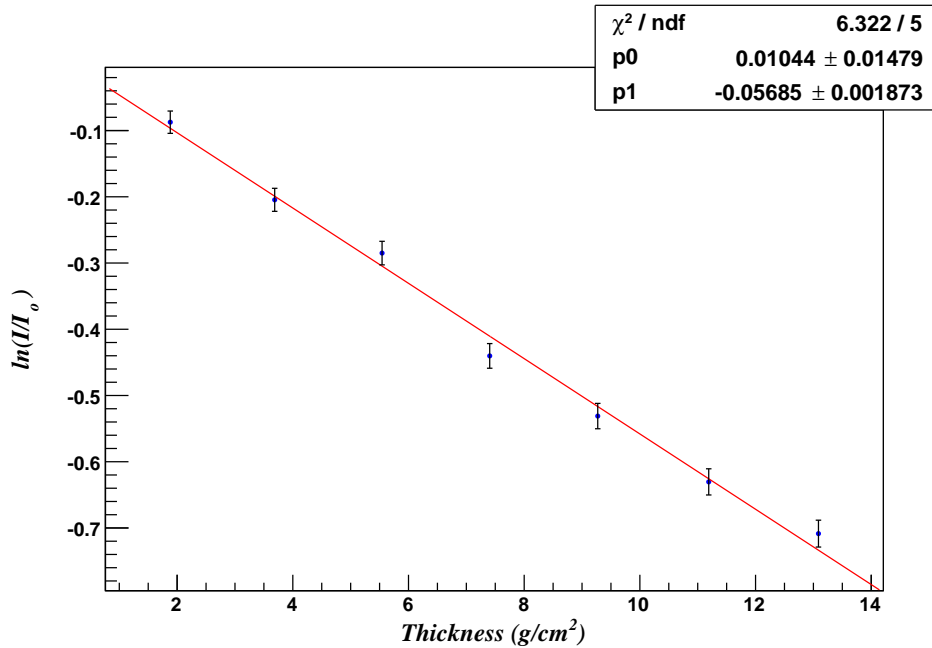


Figure 16: Mass absorption coefficient is the p1 parameter in this case. The graph is of $\ln(I/I_0)$ vs thickness using ⁶⁰Co peak with $E = 1.33$ MeV

Appendix: Table of Mass Attenuation Coefficients for Lead

The following data is taken from [2].

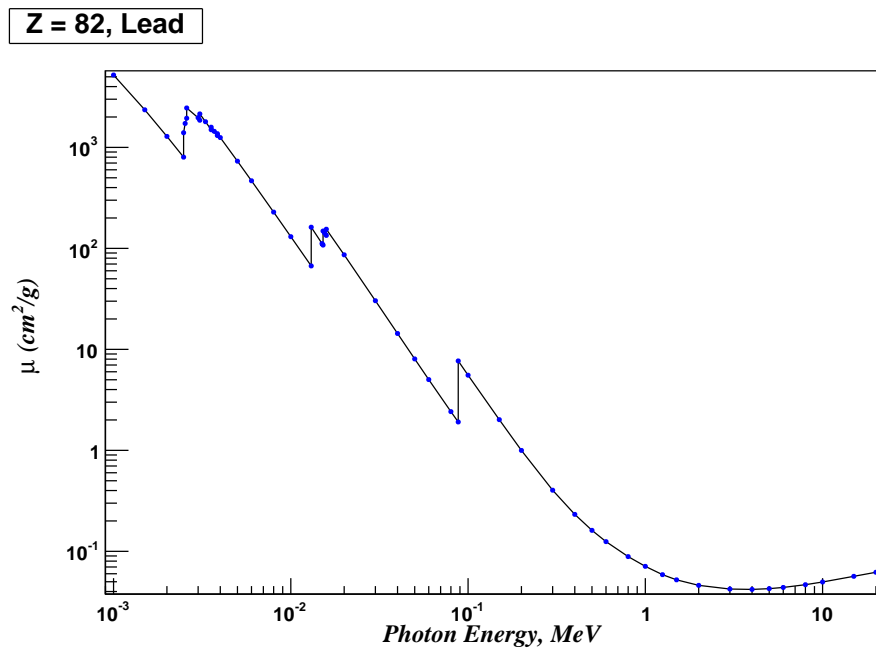


Figure 17

Energy (MeV)	μ (cm ² /g)	Energy (MeV)	μ (cm ² /g)
1.00000e-03	5.210e+03	1.58608e-02	1.548e+02
1.50000e-03	2.356e+03	2.00000e-02	8.636e+01
2.00000e-03	1.285e+03	3.00000e-02	3.032e+01
2.48400e-03	8.006e+02	4.00000e-02	1.436e+01
2.48400e-03	1.397e+03	5.00000e-02	8.041e+00
2.53429e-03	1.726e+03	6.00000e-02	5.021e+00
2.58560e-03	1.944e+03	8.00000e-02	2.419e+00
2.58560e-03	2.458e+03	8.80045e-02	1.910e+00
3.00000e-03	1.965e+03	8.80045e-02	7.683e+00
3.06640e-03	1.857e+03	1.00000e-01	5.549e+00
3.06640e-03	2.146e+03	1.50000e-01	2.014e+00
3.30130e-03	1.796e+03	2.00000e-01	9.985e-01
3.55420e-03	1.496e+03	3.00000e-01	4.031e-01
3.55420e-03	1.585e+03	4.00000e-01	2.323e-01
3.69948e-03	1.442e+03	5.00000e-01	1.614e-01
3.85070e-03	1.311e+03	6.00000e-01	1.248e-01
3.85070e-03	1.368e+03	8.00000e-01	8.870e-02
4.00000e-03	1.251e+03	1.00000e+00	7.102e-02
5.00000e-03	7.304e+02	1.25000e+00	5.876e-02
6.00000e-03	4.672e+02	1.50000e+00	5.222e-02
8.00000e-03	2.287e+02	2.00000e+00	4.606e-02
1.00000e-02	1.306e+02	3.00000e+00	4.234e-02
1.30352e-02	6.701e+01	4.00000e+00	4.197e-02
1.30352e-02	1.621e+02	5.00000e+00	4.272e-02
1.50000e-02	1.116e+02	6.00000e+00	4.391e-02
1.52000e-02	1.078e+02	8.00000e+00	4.675e-02
1.52000e-02	1.485e+02	1.00000e+01	4.972e-02
1.55269e-02	1.416e+02	1.50000e+01	5.658e-02
1.58608e-02	1.344e+02	2.00000e+01	6.206e-02

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