(Revised 1/21/98)

INTERACTIONS OF GAMMAS

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Abstract

In this experiment a Sodium Iodide Scintillator is used to both detect and measure gammas in the range of 22 keV to 2.6 MeV. The experiment is to study the interactions of gammas in various materials and in the detector itself.

Theory

A photon can interact with matter by a number of competing mechanisms. The interaction can be with the entire atom, as in the photoelectric effect, or with one electron in the atom, as in the Compton effect, or with the atomic nucleus (as in pair production). The probability for each of these competing independent processes can be expressed as a collision cross section per atom, per electron, or per nucleus in the absorber. The sum of all these cross sections, normalized to a per atom basis, is then the probability that the incident photon will have an interaction of some kind while passing through a very thin absorber which contains one atom per cm^2 of area normal to the path of the incident photon.

The total collision cross section, σ, per atom when multiplied by the number, n, of atoms per cm^3 of absorber is then the linear attenuation coefficient, μ_0 per centimeter of travel in the absorber. The fraction of incident photons which can pass through a thickness x of absorber without having an interaction of any kind is given by

$$I_0 = e^{-\mu_0 x} = e^{-\sigma n x} \quad .$$

We sometimes wish to express the absorption in terms of the equivalent matter traversed, namely $\xi = \mathrm{gm/cm}^2$. Then the thickness of the material can be expressed by $d\xi$, where:

$$d\xi = \rho dx.$$

The <u>mass</u> absorption coefficient is defined by:

$$\mu_m = \frac{\mu_0}{\rho},$$

so that the fraction of the beam not absorbed is:

$$\frac{I}{I_0} = e^{-\mu_m \xi} \quad .$$

In this experiment we will measure the mass absorption coefficient of materials of different Z for gamma rays of a large range of energies. We will try to understand these results in terms of what we know about the interactions of gamma rays with matter.

As mentioned above, there are three mechanisms of interaction which are important at the gamma ray energies we are interested in: photoelectric effect, pair production, and Compton effect. These are described briefly below. You should also read Eisberg and Resnick, p. 53–56 and/or Evans, Chapters 23 and 24.

- Photoelectric Effect
  In this interaction the photon ejects an electron from an atom (generally from the K or L shells). The photon is completely absorbed and all its energy is transferred to the atomic electron. The atom then emits characteristic X–rays and Auger electrons as it returns to normal.

- Pair Production
  In pair production a photon of sufficiently high energy is annihilated and an electron–positron pair is created. For a free photon conservation of energy and momentum would not be possible, so pair production must take place in the field of a nucleus (or of another electron) which will take up the balance of momentum. The energy threshold for this process is $2mc^2$ or 1.02 MeV.

- Compton Effect
  In the Compton effect the gamma ray scatters off of a loosely bound electron and loses only part of its energy. The electron recoils in one direction and the gamma goes off in another direction with a reduced energy.

The following figure (1.1) (from Evans, p. 712) provides a guide to the relative importance of these three principal interactions over a wide range of energy, $h\nu$, of the incident photons and atomic numbers, Z of the attenuating material.

Knowledge of these interactions will also be important in understanding the detection of gammas with a scintillation detector.

Detection of Gammas – Scintillation Detectors

Gamma rays may be detected in a number of ways, including gas–filled counters, sold–state detectors, and scintillation detectors. This experiment makes us of a scintillation detector.

In a scintillation detector the gamma ray passes into an organic or inorganic crystal where it interacts with the atoms of the crystal by one of the above interactions. The result of these interactions are the production of charged particles (electrons and gammas) and scattered gammas. The scattered gammas travel a distance through the crystal which depends on their energy and they may or may not interact again before leaving the crystal. The charged particles travel a relatively short distance through the crystal leaving behind a trail of exited atoms. A few materials will emit light in the UV and visible wave lengths as the excited atoms return to the ground state. These “scintillations” are detected by a

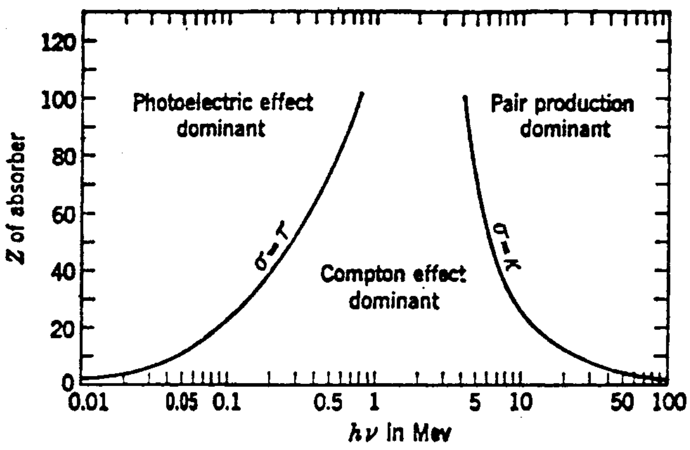


Figure 1.1: Relative importance of the three major types of γ-ray interaction. The lines show the values of Z and $h\nu$ for which the two neighboring effects are just equal.

photomultiplier attached to the crystal. Materials to be used as scintillators must of course be transparent to their own light so that it can be seen by the photomultiplier. A discussion of organic and inorganic materials suitable for scintillators is given in an appendix. In this experiment we use an inorganic crystal, NaI, as a scintillator.

If monoenergetic gammas interact in the NaI crystal the pulses produced by the photomultiplier will not all be if the same height but will show a certain distribution in height. A "pulse height spectrum" is obtained by plotting a graph of the number of pulses per unit time versus pulse height. The feature of these pulse height spectra can be understood in terms of the interaction the gamma undergoes in the crystal.

In the photoelectric effect and pair production all of the gamma ray energy in converted to electron (or positron) energy. Path lengths of charged particles are short so there is a good chance for all of the energy being absorbed in the crystal. In Compton scattering, however, part of the energy is converted to electron energy and part remains in the scattered photon. The scattered photon may interact again in the crystal by a second Compton scattering or by photoelectric absorption, but in some cases the scattered gamma ray escapes the crystal, carrying its energy with it.

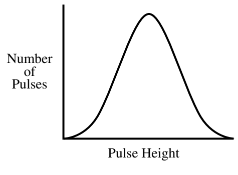
If all the gamma ray energy is captured in the crystal there will still be a pulse height distribution of finite width due to a number of effects which depend on the location of the events in the crystal:

1. Inhomogeneities in the crystal.

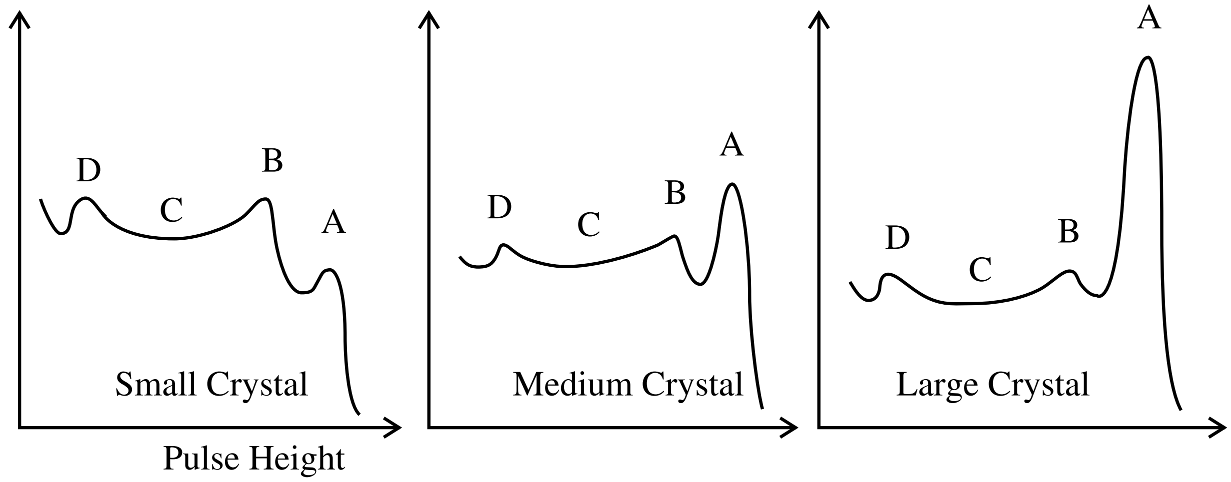
2. Variations in reflections from the walls.

3. Variations in photocell sensitivity.

4. Statistical fluctuation due to the moderate number of photoelectrons in the photomultiplier. The pulse height spectrum in this case would look like:



In practice, however, because of the finite size of the crystal some of the Compton scattered gammas will escape the crystal and in this case the spectra will look like these:



The peak A corresponds to interactions in which no gamma escapes. The peak B and the plateau C correspond to Compton interactions in which the scattered gamma escapes the crystal. B is called the "Compton Edge" and corresponds to a Compton scattering in which the gamma is scattered in the backward direction and then escapes the crystal. In this case the photon transfers a maximum amount of energy to the electron so that a minimum of energy escapes. Small peaks and bumps like that at D may be caused in various ways:

(D1) Photoelectric interactions in the source itself or in the shielding can give K–shell X–rays. These are then detected in the usual manner by the detector at energies around 20 to 50 keV.

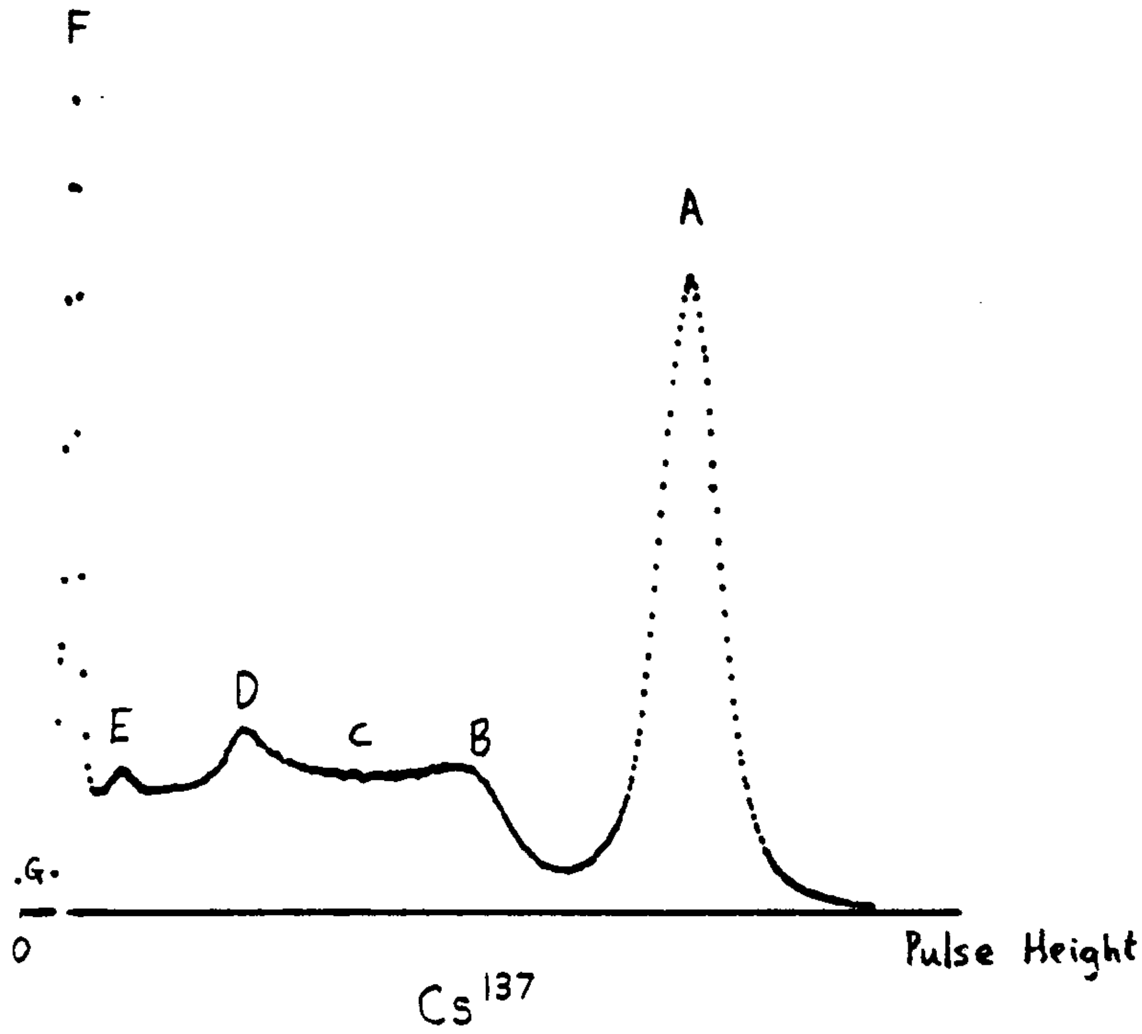
(D2) Gammas may Compton scatter (even backwards) from the shielding or photomultiplier glass and enter the crystal and be detected. The energy is dependent upon the angle and the energy of the original gamma.

(D3) A small group between B and A can be caused by a K–shell X–ray escaping from the crystal after a photoelectric interaction in the crystal.

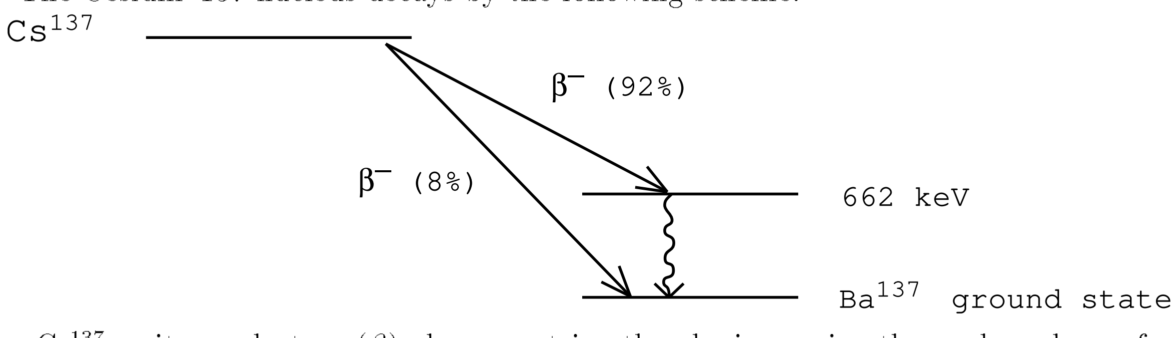
All of the above defects (except 1) are reduced by using larger (and more expensive) crystals which have a higher probability of both capturing the original gammas and also capturing scattered gammas which might otherwise escape.

A Typical Spectrum

The following figure shows a typical spectrum obtained with a 5.1 cm $\times$ 5.1 cm NaI scintillator and a Cs^{137} source.



The Cesium–137 nucleus decays by the following scheme:



The Cs^{137} emits an electron (β) plus a neutrino thereby increasing the nuclear charge from 55 to 56 by changing a neutron to a proton.

$$Cs^{137} \rightarrow Ba^{137} + e^- + \bar{\nu}_e$$

In 92% of the decays only 514 keV is transferred to the electron and neutrino and the Ba^{137} is left in a metastable, excited state. This decays ($T_{\frac{1}{2}} = 2.6$ min.) by either emitting a <u>662 keV</u> gamma (90%) or "internally converting" the gamma (10%) before it leaves the Ba atom and ejecting a K shell electron instead. In effect, the gamma interacts with the K shell electron as the gamma is created by the nucleus. In this case a fast electron is thrown out and then followed by a 32 keV x–ray as the K shell of the Ba is refilled.

The spectrum shows the following features:

A. This is due to the complete absorption of 662 keV gamma, usually a Compton scatter followed by a second scatter and/or a photoelectric interaction. The lead shielding collimates the incoming gammas so that all strike near the center of the NaI crystal and so are unlikely to escape without a second interaction. The NaI absorption of 662 keV gammas follows the equation

$$N(x) = N_0 e^{-x/d} \quad .$$

where d = 3.7 cm. However scattered gammas are much more likely to interact. For example, if the energy of the scattered gamma is 300 keV then d = 1.6 cm.

B. "Compton Edge". The gammas which are scattered once and then escape can transfer a maximum of 478 keV by being scattered backwards ($\theta = \pi$).

C. This region is due to single Compton scatters with $0 < \theta < \pi$. The region extends from the Compton edge to zero energy.

D. This peak is due to gammas which have been scattered through $0 < \theta < \pi$ outside the crystal. For example some 662 keV gammas leave the source and strike the lead at the back of the cavity holding the source. The 662 keV can be scattered forward with an energy of 184 keV and pass into the detector where it will be detected. Alternatively a 662 keV gamma may pass through the crystal without interaction and then be backscattered from the front face of the photomultiplier back into the detector crystal.

E. The lead shielding can produce X–rays by electrons returning to the K–shell after they have been ejected by a photoelectric interaction with a gamma ray. The K_α X–rays from lead have an energy of 75 keV.

F. This peak is due to the 32 keV X–rays produced by Ba^{139} after internal conversion.

G. Pulses smaller than 20 keV can be produced by photomultiplier noise and so the LLD of the detector has been set to remove these.

Useful Gammas

Energy (keV)	Source	Lifetime	% Giving Gamma	Origin or Comment
2614.4*	Th^{228}	1.9 y		Gives a range of 84 through 2614 keV
2204.2	Ra^{226}	1600 y		(From daughter Bi^{214})
1769.7	Ra^{226}	1600 y		(From daughter Bi^{214})
1332.5*	Co^{60}	5.3 y	100	
1274.5	Na^{22}	2.6 y	100	
1173.2*	Co^{60}	5.3 y	100	
661.6*	Cs^{137}	30 y	85	
511.0*	Na^{22}	2.6 y	180	From positron-electron annihilation
356*	Ba^{133}	10 y		
302	Ba^{133}	10 y		
280*	Se^{75}	120 d	25	
265	Se^{75}	120 d	60	Replace each 2 years
136	Se^{75}	120 d	57	
122*	Co^{57}	23 d	98	
87.7*	Cd^{109}	1.3 y	1.0	K-X-ray from Ag^{109} after K capture
81.0*	Ba^{133}	10 y		
75.0				K-X-ray sometimes from Pb shielding
59.5*	Am^{241}	458 y	36	
32.1*	Cs^{137}	30 y	6.8	K-X ray from Ba^{137} after internal conv.
31	Ba^{133}	10 y		K-X-ray from Cs^{133} after K capture
22.1	Cd^{109}	1.3 y	25	K-X-ray from Ag^{109} after K capture

y = year
d = day

The table of available gammas gives 18 energies. However, some are closer together and since there is little point in using energies within 5% of each other, you should choose about 13 energies such as those marked *.

Apparatus

Gamma Ray Sources

A number of radioactive sources (Th^{228}, Ra^{226}, Cs^{137}, Ba^{133}, Cd^{109}, Se^{75}, Co^{60}, Co^{57} and Na^{22}) are available mounted in small plastic rods and are kept in a lead container in Room 2507. Most of them are supplied by Isotope Products Labs. The sources are not strong (1–100 μCi but they could interfere with the counting in this experiment and for this reason they should be kept inside the shielding when not in use.

Gamma Ray Detector

The gamma ray detector is a scintillation detector consisting of a scintillation crystal, a photomultiplier tube, and a preamplifier assembled in a single unit supplied by a Mech–Tronics Nuclear. The crystal is a 2 inch diameter, 2 inch thick NaI crystal doped with thallium. The photomultiplier is an RCA 8053 with 10 dynodes and a maximum voltage rating of 1500 volts. The photomultiplier anode output is connected to an amplifier by a short length of coaxial cable.

During operation, the crystal absorbs energy from a gamma event and produces a proportional flash of light. The light flash causes the photomultiplier tube cathode to emit a proportional quantity of electrons. These are attracted from dynode to dynode through the tube with a multiplication effect at each successive dynode due to secondary emission. The highly intensified burst of electrons which arrives at the anode of the tube, still proportional to the energy of origin, is transferred to form a charge at the input capacitor in the preamplifier. The amplifier responds by creating a positive output pulse which retains the basic proportional significance.

There are two connectors on the photomultiplier tube base:

- Anode Output: Connects photomultiplier output pulses to the amplifier. This output pulse is always negative and has an amplitude depending on the input pulse and the HV of the photomultiplier. The connection between the photomultiplier output and the amplifier input is always made with a 50 ohm coaxial cable.

- HV: Connects the high voltage power supply to the photomultiplier tube, using HV BNC for the white HV cable.

Amplifier

The amplifier is an ORTEC unit. Usually you will find the model 575A. The amplifier accepts both positive or negative input pulses and provides both pulse shaping and amplitude expansion of these pulses. The amplifier gain is set via a control knob setting and there are both unipolar positive and bipolar positive going outputs on BNC connectors. The function of the amplifier is to produce positive output pulses of suitable amplitude and shape so that they can be fed into the pulse height analyzer.

Multi–Channel Pulse Height Analyzer

The multichannel analyzer is a PC containing an ORTEC model 916A pulse height analyzer card (MCA) run by the Maestro II software package. The MCA card contains an Analog to Digital Converter (ADC), single channel analyzer (SCA), multichannel scaler (MCS), and a dual–ported memory. The card, along with the standard software, transforms the personal computer into a multichannel analyzer. An input of 0 to 10 volt positive pulses from a shaping amplifier is the only external signal necessary for pulse height analysis operation. For further details consult the manual for the 916A and the manual for the Maestro II software which runs the MCA board. The software is located in the MCA directory and is started by typing **MCA** on the command line. The MCA has been set up for the input voltage range of 0 to 10 Volts to correspond to channel 0 (0 V) and channel 512 (10 V).

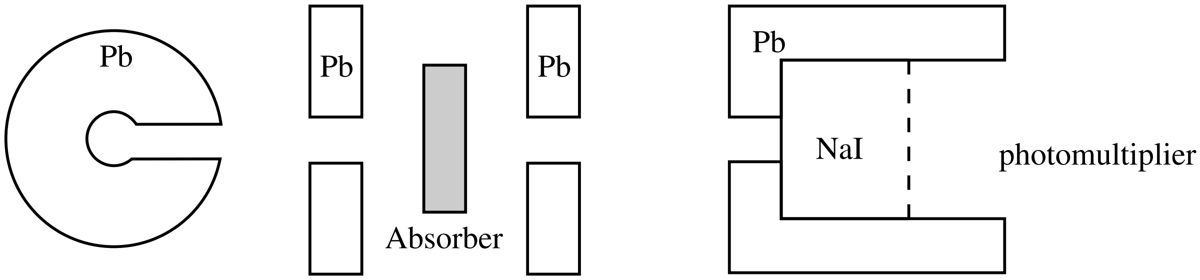
High Voltage Supply

The high voltage supply for the gamma ray detector is usually a Hewlett Packard Model 6522A using the positive HV output connector. The supply can furnish an output of $\pm$ 0 – 2000 V DC. We normallly run the photomultiplier somewhere between 800-1000 Volts.

Oscilloscope

Any mobile scope may be used to display the pulses being input to the multi–channel pulse height analyzer.

Lead Collimators



The source is placed in the center of a lead cylinder so that gamma rays may pass freely:

- through a side hole in the cylinder.
- through a second collimating hole in a circular lead plate.
- through any absorber.
- through a third collimating hole in a second circular lead plate.
- through a fourth hole in the lead shielding the NaI detector.

The purpose of the 4 collimating holes is to insure that only gammas which are not scattered may reach the detector. Once a gamma ray has been scattered by the lead or by the absorber, then it is unlikely to reach the detector. The NaI crystal has a diameter of 5.1 cm but the entry hole in the lead has a diameter of only 3.2 cm. This is to insure that the gammas which enter the NaI have a high probability of losing all their energy in the NaI.

Procedure

A. Set up the system

1. Connect the "Output" connector of the detector to the DC input of the amplifier. Set the input polarity switch to "neg" and use the "Uni" output.

2. Connect the output of the amplifier to the BNC connector labeled "ADC" on the MCA card located in the rear of the PC.

3. Connect the high voltage supply to the "HV" connector on the detector using the white HV cable with HV BNC connectors. Turn it on and set to about +800 volts to start.

4. Place a Cs^{137} source with a strength near 100 μCi in the cylinder and check the pulses from the preamplifier and amplifier with a scope. Note the amplitude and width of the pulses.

Take Care

The gamma sources used in this experiment have strengths of up to 100 μCi. Although these are relatively safe sources, you should act as if they are stronger.

1. Never leave sources lying about. They should be taken from their lead storage container directly to the cylindrical lead mounting or vice–versa.

2. Handle the sources by the clear plastic rods.

3. Report a missing source immediately.

4. Use the survey meter to check radiation levels around the sources.

B. Observe some typical spectra

1. Observe the spectrum of pulses from the Cs^{137} source. Adjust the amplifier gain so that the peak at 662 keV is located in the upper half of of the available range. Collect enough data to smooth out the statistical fluctuations. Print out the spectrum and tape it in your data book. Identify the features of the spectrum.

2. Collect and record the spectra from a few other isotopes, such as Na^{22}, Co^{60}, Ba^{133}, and Th^{228}. Always adjust the gain so that the significant peaks are within the range of the analyzer.

C. Measure the attenuation in Aluminum of 662 keV gamma rays

1. Measure the intensity of gammas transmitted through 7 or 8 different thicknesses of Al using the gammas in the 662 keV peak from Cs^{137}. Set up the 662 keV peak as a "Region of Interest" (ROI) and use "Sum" counts as your measure of intensity. Does this properly correct for the background counting rate?

2. Plot the intensity of the 662 keV peak as a function of thickness of A1 on semi–log paper. Draw a straight line through the data points and from the slope of the line determine the linear attenuation coefficient of A1 for 662 keV gammas. Taking the density of Al to be 2.70 g/cm^3, calculate the mass attenuation coefficient. Compare your result to that quoted in Melissinos, p. 208.

3. Using SigmaPlot, fit the above data to a straight line with a least squares fit. Have the computer calculate the slope and the standard deviation of the slope. How does this value of the slope compare with that which you determined graphically?

D. Measure the attenuation in Al as a function of the energy, E, of the gammas.

1. Some gamma ray sources available in the lab and the energy of their gammas are listed in the accompanying table. The most useful of these are indicated with an asterisk. Measure the attenuation in Al of these gammas. You need only measure the transmission for one thickness at each energy. Because the transmission varies so much with energy, the thickness required for an accurate measurement will vary with energy. The optimum thickness for determining the transmission with maximum accuracy in a given counting time is that thickness which gives a transmission of 37%. Can you prove this? In order to get the various peaks at a reasonable channel position for measurement, you will have to change the gain of the amplifier as you change the energy of the gammas.

2. Calculate the mass attenuation constant, μ_m, at each energy and plot your results as a function of energy.

E. Measure the attenuation of 662 keV gammas in materials of different Z.

1. The absorbing materials available in the lab are listed in the accompanying table, along with their density, atomic number, and the energy corresponding to their K–shell absorption edge. Measure the transmission of each of these materials for the 662 keV gamma ray from Cs^{137}.

2. Calculate the mass attenuation coefficient for each material and plot your results as a function of the atomic number Z, of the material.

F. Comment on the following:

1. The Z dependence of the Compton scattering at about 500 keV.

2. Any indication of pair production.

3. The Z and E dependence of the photo–electric effect.

Be prepared to answer questions on the following:

1. The effectiveness of the lead shielding.

2. The shape of any gamma spectrum.

3. The principle of operation of a multichannel analyzer.

4. The principle of operation of the photomultiplier.

5. The K absorption edge of lead is at 88 keV yet it emits X–rays at only 75 keV.

Absorber	**Z**	Density (gm/cm^2)	K-shell Edge (KeV)
Wax $(CH_2)_n$		2.71	
Lucite $(C_5H_8O_2)$		1.16-1.20	
Be	4	1.848	0.111
C (graphite)	6	1.5	0.284
Al	13	2.70	1.56
Fe	26	7.86	7.114
Ni	28	8.90	8.333
Cu	29	8.96	8.999
Mo	42	10.2	20.00
Sn	50	7.29	29.20
W	74	19.1	69.52
Au	79	19.3	80.72
Hg	80	13.55	83.10
Pb	82	11.35	88.10
U (depleted 238)	92	18.9	115.6

References

1. R.D. Evans, "The Atomic Nucleus" McGraw Hill, (1955).
2. Eisberg and Resnick, "Quantum Physics" Wiley, (1974).
3. R.D. Evans "Gamma Rays" Chap. 8e in "American Institute of Physics Handbook", 3rd Ed., McGraw–Hill, (1972).

Appendix

Scintillator Materials

1. **Organic Scintillators** These are the cheapest. Examples are:

   (a) Anthracene crystals.

   (b) Stilbene Crystals.

   (c) Polystyrene with traces of Terphenyl and POPOP.

   (d) Xylene or Toluene with traces of Terphenyl and POPOP.

   (e) Various commercial plastic scintillators such as NE102.

   Organic scintillators give fast light pulses - about 5 to 15 nsec long. The basic material usually will absorb the light which it emits and so wavelength shifters are dissolved in the liquid (or plastic) to absorb the short wavelengths and re–emit them with longer wavelengths. The wavelength shifters are usually very complex aromatic substances and are used in very dilute concentrations.

   The wavelength shifters also absorb UV (from sunlight or the fluorescent lights) and emit a very pleasant and characteristic blue glow.

   Organic scintillators have 3 disadvantages:

   (a) Their efficiency of conversion (particle energy loss to light output) is lower than for NaI (see below).

   (b) Their conversion is not as precise as for NaI. Identical particles giving the same energy loss E in an organic scintillator will result in various light outputs with a $\pm$ 10% variation.

   (c) When compared with inorganic scintillators such as NaI or CsI, organic scintillators have both lower mass densities and lower average atomic numbers Z. Hence the organic scintillators interact less with gammas (to produce free electrons and ionization) and are usually not used as gamma detectors.

2. **Inorganic Scintillators**

   The best are single crystals of ZnS, NaI, CsI or BaF. The light output can be sometimes increased by doping (or "activating") the crystal with an element such as thallium. This experiment uses a 5.1cm $\times$ 5.1 cm cylinder of NaI with about 0.1% Tl. The Tl increases the light output by about 15%.

   Inorganic scintillators give a larger and more precise light pulse than organic scintillators. However, the light pulse is emitted over a longer time, about 1 μsec and so NaI is not as useful for fast coincidence work as organic scintillators.

   Read Melissinos 194-196.