Experiment 352: Interaction of γ Rays with Matter

Aims

1. To test the exponential attenuation law for a beam of radiation.
2. To measure the attenuation coefficient (μ) of 0.662 and 1.333 MeV γ rays in aluminium and lead.

References

1. R.D. Evans, "The Atomic Nucleus", McGraw-Hill
2. A.C. Melissinos, "Experiments in Modern Physics", Academic Press
3. E. Bleuler and G. J. Goldsmith, "Experimental Nucleonics", Rinehart

Introduction

As well as being of basic physics interest, photon interactions in matter must be understood for a number of applications such as medical radiology, industrial inspection and processing, nuclear power reactor core and shielding design, and the interpretation of nuclear and particle physics experiments. The interactions of photons with matter, in which photons are removed from, or scattered out of a beam, may be classified according to:

(i) The kind of target with which the photon interacts (e.g. electrons, atoms, or nuclei)

(ii) The type of event (e.g. scattering, or absorption).

Fig. 1 shows possible interactions (from Chap.25 Sect.3 of Ref. 1).

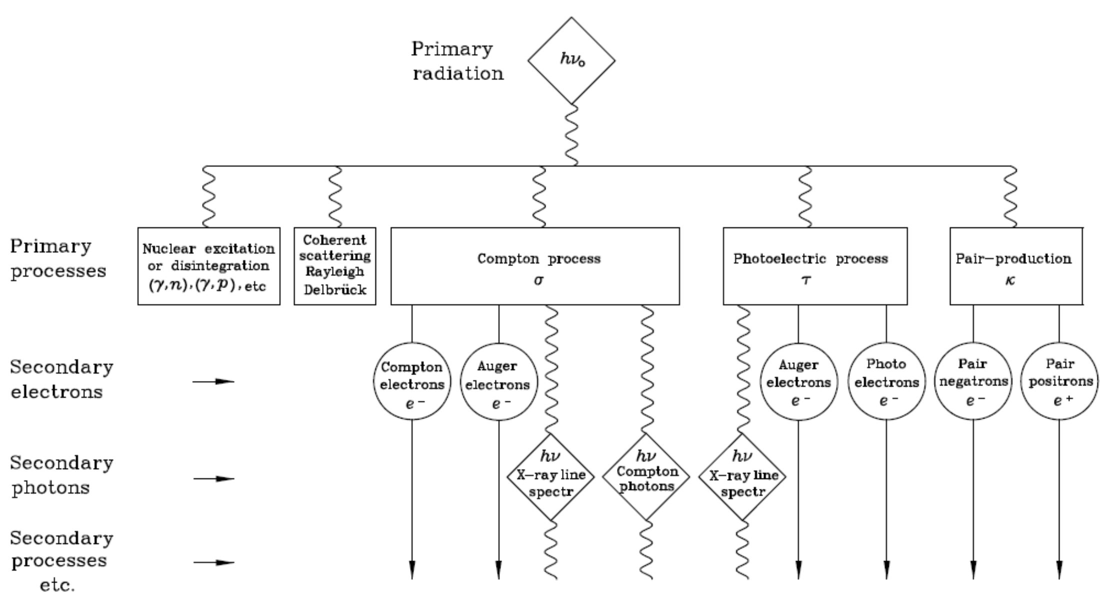


Figure 1: Interactions of γ radiation with matter

For photon energies in the MeV region, the important processes are:

(i) Compton scattering (C),

(ii) the photo-electric effect (PE) and

(iii) Electron-positron pair production (PP) (with a threshold at a photon energy of 1.022 MeV).

The cross-sections of these processes depend on both the photon energy and the atomic number of the medium with which the photons are interacting. Fig. 2 shows the energy dependence of the cross-section of lead as measured by the attenuation coefficient (defined later). See also Ch. 25 Sect. 1 of Evans (Ref.1).

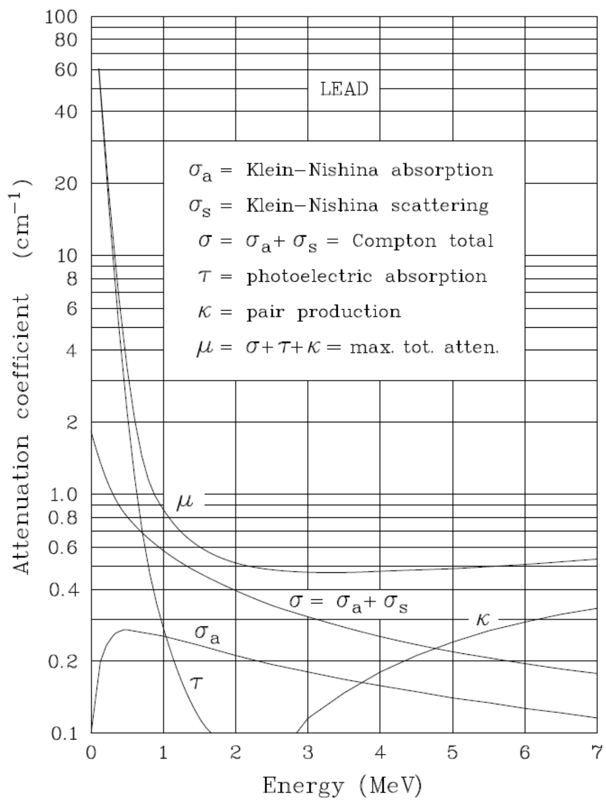


Figure 2: Attenuation due to various interactions

The total photon interaction cross-section per atom is given by:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{C}} + \sigma_{\mathrm{PE}} + \sigma_{\mathrm{PP}}$$

and represents the sum of all the elementary "scattering" processes by which a photon may be removed from the beam.

These cross-sections can be evaluated to high accuracy from fundamental theory, since they depend almost entirely on the electromagnetic interaction and are therefore within the field of Q.E.D. (quantum electrodynamics), the most accurately known of all physical theories.

Theory

Consider a slab of material of thickness t located between a narrowly collimated source of monoenergetic photons and a narrowly collimated detector as shown in Fig. 3(a). In a thin layer dx within the slab there will occur a reduction dI in the intensity I of the photon beam. This is due to the removal of photons by:

(i) outright absorption, or

(ii) scattering of the beam.

The fractional reduction of the beam intensity is proportional to the "narrow beam" attenuation coefficient μ and to the layer thickness dx:

$$-\frac{\mathrm{d}I}{I} = \mu \mathrm{d}x$$

The real physics of the interaction is in μ. Integrating this, assuming a homogeneous medium, the intensity transmitted through the slab is given by:

$$I(t) = I_o \exp(-\mu t)$$

where I_o is the intensity incident on the slab. There may also be a significant and constant background. You may need to take account of this in your data analysis.

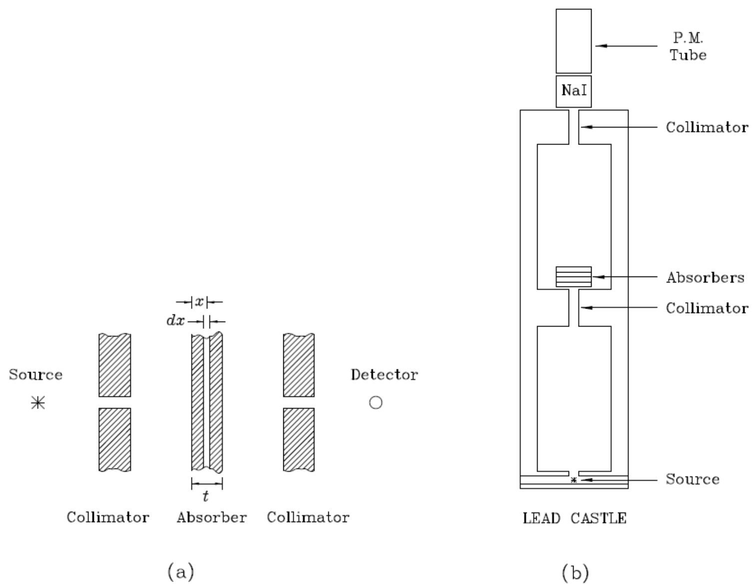


Figure 3: Schematic of experimental setup

The use of "good geometry" is important. The attenuation of the photon beam is due to the removal of photons from a geometrically well-defined beam. This is a single interaction with the material for each photon removed. Any secondary photons arising from such an interaction must not be seen by the detector.

For more complicated situations than the "narrow beam" or "good geometry" situation, the attenuation is still exponential but is modified by two additional factors. One is a geometrical factor depending on the source geometry, and involves, for example, the inserting of the inverse square law in the equation above in the case of an isotropic point source. The other is the "build-up factor", which takes into account secondary photons produced in the absorber, and which reach the detector. See Ch. 25, Sect. 3 of Evans (Ref. 1) for a discussion on "good" and "poor" geometry.

The attenuation coefficient μ defined as above has dimensions of an inverse length (e.g. cm^{-1}), and is termed a "linear attenuation coefficient". This quantity depends on the physical state and density of the medium.

A more useful quantity is the "mass attenuation coefficient" μ/ρ in which ρ is the material density. Then, the attenuation law is:

$$I(x) = I_o \exp\left(-\frac{\mu}{\rho}x\right)$$

where μ/ρ has units cm^2/g and thickness x has units g/cm^2. This mass attenuation coefficient is closely related to the total interaction cross-section per atom σ_{tot} and is given by:

$$\frac{\mu}{\rho} = \sigma_{\text{tot}} \frac{N_A}{M}$$

where N_A is Avogadro's number and M is the molecular weight of the absorber material.

If one measures the counting rate I_o in the detector with no absorber and the rate I with an absorber of known thickness, then μ/ρ and hence the total interaction cross-section $\sigma_{\rm tot}$ can be found.

Suggestions

- Consultation with your demonstrator is advised at this stage.
- Pay attention to the necessary accuracy in the statistics and to any systematic errors.
- Turn on the equipmment and allow it to warm up and stabilize before making any measurements (this can take up to an hour).
- The Multi-Channel Analyser programme `Nucleus` has an option to save the data collected. This can be useful for background correction and for finding appropriate regions of interest.

> **Note:** The two γ ray sources (^{60}Co and ^{137}Cs) are kept in the radioactive store room. The sources are on the end of metal rods which stand in a lead block. *Please ask your demonstrator to issue these out to you.* You only use one source at a time. To minimise your radiation exposure, hold the source at arm's length when you transfer it from the storage block to the lead castle. Remember the $1/r^2$ (inverse square) rule.

Experiment

1. Place the ^{60}Co source in the appropriate hole bored in the base of the castle (see Fig. 3(b)). The position of the source in the hole should be adjusted to maximize the count rate.
2. Connect up the electronics as shown in Fig. 4.

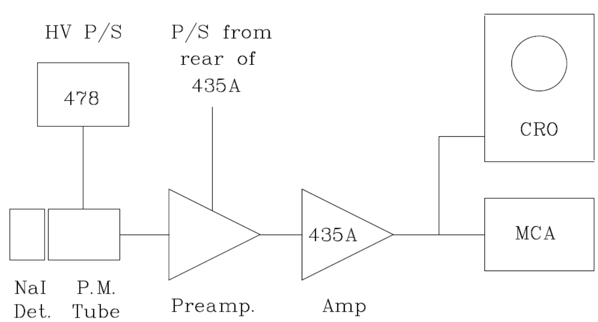


Figure 4: Instrumentation wiring diagram

Use the following initial settings:

Photomultiplier	Bias:	+1000 V
435A Amplifier	UNIPOLAR/BIPOLAR:	BIPOLAR
	POS/NEG:	NEG

Adjust the 435A gain so that the largest pulses to be observed have a pulse height of around 8 volts when viewed on the CRO. Check that they are bipolar and that the first excursion is positive. You may also like to set up the Multichannel Analyser (MCA) so that it has a dispersion of 512 channels and displays only 512 channels. For convenience adjust the gain on the 435A amplifier so that the 1.333 MeV peak lies at about channel 450.

3. It is necessary to select the "full energy" peak. This is done by setting a 'Region of Interest', and using a linear scale on the MCA. You will also need to arrange to count for a preset time. Ensure that you choose the correct peak when working with the ^{60}Co source. See Appendix for more details.

4. Measure the counting rate as a function of absorber thickness for both absorbing materials (aluminium and lead). It is important to correct for the background rate in the energy range of interest, and you should devise a way of doing this with sufficient accuracy to obtain the net counting rate.

   Make your measurements in such a way that the effects of any drifts in the electronic system are minimized. You may need to consult your demonstrator.

   You should be able to achieve an accuracy in the attenuation coefficients of better than 1 %. Pay attention to the necessary accuracy in the timing and in the statistics of the counting, and to the background subtraction.

5. Repeat the above procedures for the ^{137}Cs source.

6. Plot suitable graphs to display your data.

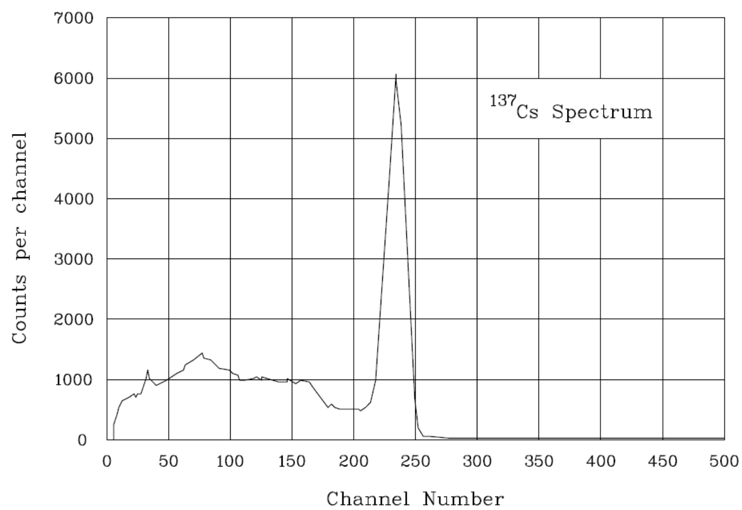


Figure 5: Spectrum of γ radiation from ^{137}Cs

7. Extract from your data best estimates of the mass attenuation coefficient μ/ρ and the total cross-section for both elements. You may wish to analyse the results with PYTHON. If you linearise the problem, you could use the `regress` function:

   `regress(x,y,sy,n)`
   where `sy` = errors in y values and `n` = order of polynomial.

   Ensure that you use correctly calculated errors and calculate chi-squared.

Questions

1. Explain the shapes of the pulse-height spectra of the γ rays (see Fig. 5).

2. Why is it desirable to use only the events in the total energy peak for the measurement of the attenuation coefficient?

3. Discuss the effects on your results of impurities in the aluminium absorbers.

4. Comment on the nature of your graphs of counting rate versus absorber thickness.

5. Calculate the Compton cross-sections for 0.662 MeV rays in aluminium and lead. Use the Klein-Nishina formula (see Ref 1) for the total Compton cross-section σ_{KN} per electron.

   Explain carefully the agreement or disagreement of these calculated values with your measurements.

Evans, pp 715, 716 gives plots of attenuation coefficients in aluminium and lead.

Appendix

The “Gamma Acquisition” Software

This is a quick guide to the “Gamma Acquisition” software for Expt 352. For a more thorough introduction, please see other lab handouts which use the same programme, such as Expt 252: Relativistic Electrons.

You should find an icon called ‘Gamma Acquisition and Analysis’ on the Windows desktop.

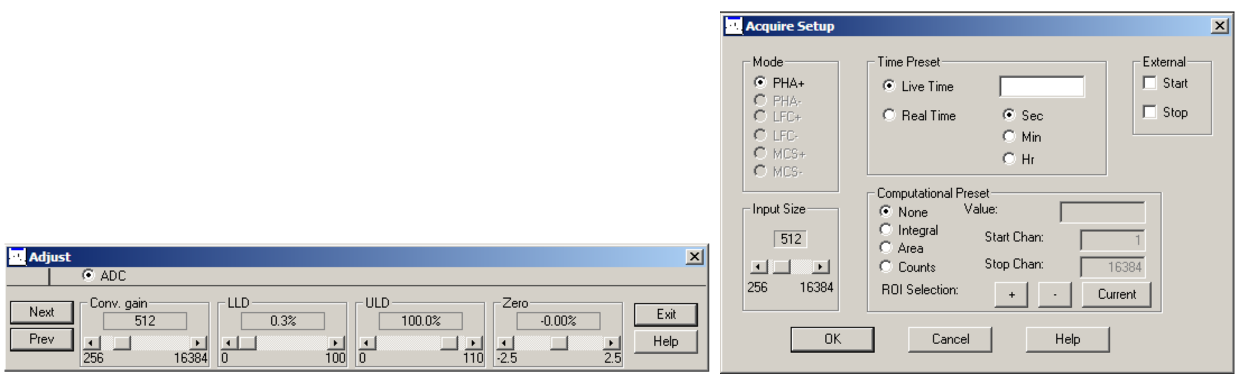
In order to collect data, you must open a detector data source:

– Select File – Open Datasource ... from the menus.

– Click the Source:Detector radio button.

– Select MP2_MCA1 and then click Open.

If you want to set the MCA to 512 channels, go to go to MCA – Adjust and set Conv. gain. It is fine to work with a larger number of channels (up to 16384), but that level of resolution is not required for this experiment. Then go to MCA – Acquire Setup and also configure Input size. You need to collect data for a certain amount of time, so specify this in the Live Time box.



(a) (b)

Figure 6: Settings

You can now use the buttons under Acquire to collect data (Fig. 7).

After you collect your data, move the and markers to highlight in red the region of interest (ROI). The is your “cursor”. Note that the x-axis shows the channel number which corresponds to the energy of the γ ray. The y-axis shows the number of counts of that channel.

Click Next or Prev to analyse your data. Record the Integral value, which is the number of counts within that ROI. In the Caesium example (Fig. 7), there are 47961 occurrences of 0.662 MeV γ-ray interactions in 600s.

You can save your data as *.CNF files (used by this programme) or *.TKA files which can be imported into PYTHON.

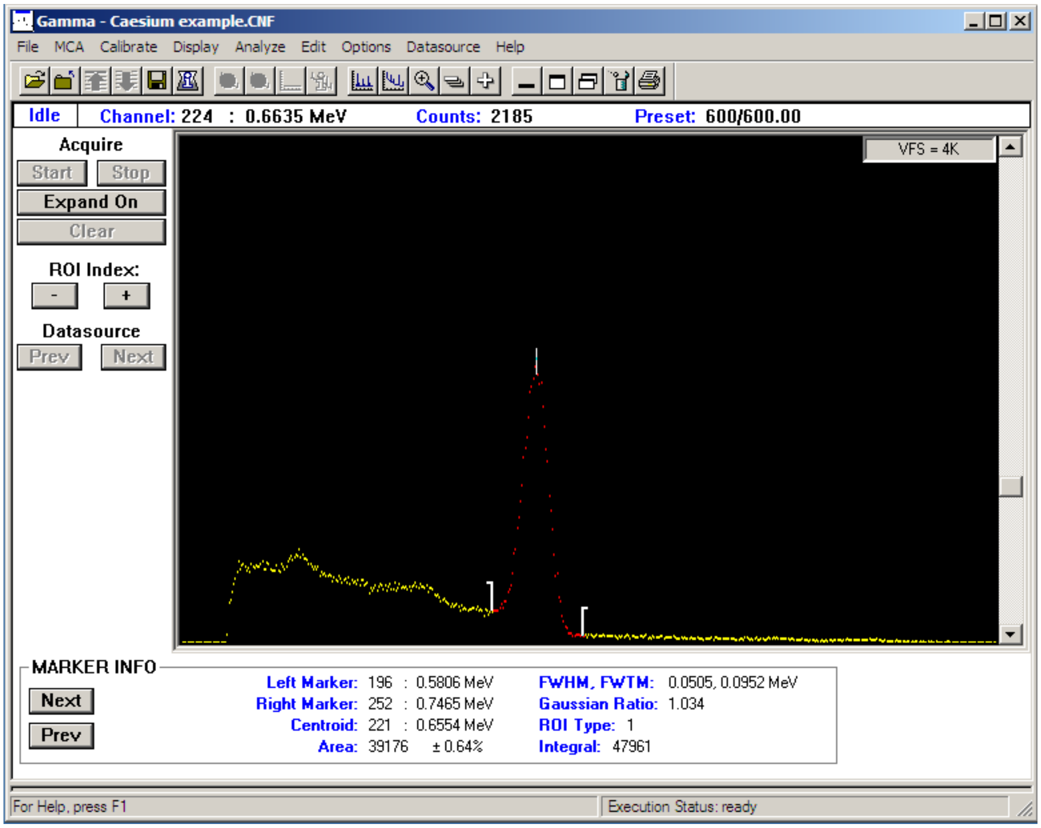


Figure 7: Caesium

Absorbers

The **absorbers** have been machined very carefully, so they have uniform and accurately measurable thicknesses.

PLEASE HANDLE THEM CAREFULLY.

1. Aluminium

These are made of an alloy whose composition is:

Aluminium: 99 % Silicon: 0.5 % Magnesium: 0.5 %

The plates all have a thickness of 10.00 ± 0.01 mm, uniform over the surface to about 0.01 mm. They have a density of $2.558 \pm 0.001\,\mathrm{g/cm^3}$.

In order to protect their surfaces they have been "anodised", a process which hardens the surface. (The black colouring has been introduced during the anodising.) The process occurs through about a micron on the surfaces.

2. Lead

These are discs of about 25 mm diameter fixed into anodised aluminium blocks. They are made in two thicknesses: 10.03 ± 0.02 mm and 4.98 ± 0.03 mm. Take their density as $11.25 \pm 0.01\,\mathrm{g/cm^3}$.

List of Equipment

1. γ ray source, ^{60}Co (1.333 MeV at 37 MBq) and ^{137}Cs (0.662 MeV at 300 μCi, 11.1 MBq)
2. Sodium iodide scintillator and photomultiplier assembly
3. Aluminium and lead absorbers
4. A lead "castle" for collimation of the ray beams, and mounting of absorbers and detectors
5. ORTEC Model 478 High Voltage Power Supply
6. ORTEC Model 435A Amplifier
7. MCA (PC with Nucleus PCAII-1000 card)
8. Hitachi 1065A Oscilloscope

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