DETECTION OF GAMMA RADIATION

FYSZ460 Syventävien opintojen laboratoriotyöt

1. Introduction

Detection of gamma radiation is one of the most important research tools in nuclear physics. Detection of gamma radiation yields information on various properties (excitation energies, angular moments, decay properties etc.) of states in nuclei. In this laboratory work you will become familiar with two different detectors used for observing gamma radiation (scintillation and semiconductor detectors) and compare the properties of these detectors. When doing this, you'll also get acquainted with some simple research methods and basic electronics as well as signal-handling techniques used in nuclear physics. Tuning of the measurement setup relies heavily on the use of the oscilloscope. The amount of material in this manual is quite large: If all the measurements are made, 4 crp's (2 ov) are credited. If a smaller baggage is desired, about one half of the measurements are selected.

2. Interaction of radiation and matter

Detection of gamma radiation is based on the interaction between the radiation and the detector material. The photon scatters from the electrons of the material (so called Compton scattering), and in each scattering process it loses a part of its energy. If the piece of material is large enough and the scatterings take place suitably, all the energy of the initial gamma ray is absorbed in the material. Thus, the energy of the photon is found by measuring the energy absorbed by the material. How this energy is determined, depends on the detector type and its functioning. Fig. 1 presents various processes that occur when a photon interacts with matter.

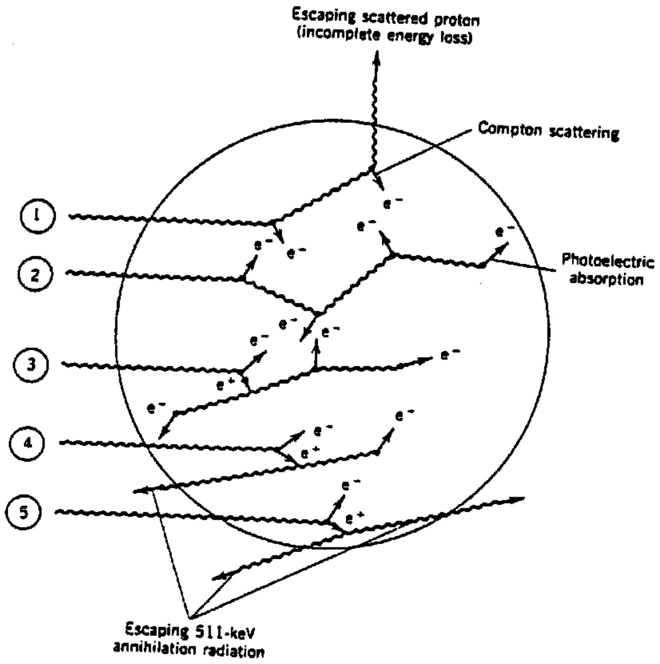


Figure 1. Processes occurring in the detection of gamma radiation

1) The most typical situation, where the photon Compton scatters a few times and the residual photon escapes from the detector.
2) The photon Compton scatters several times and gets completely absorbed in the detector.
3) If the photon is energetic enough (E > 1,022 MeV), it can form an electron-positron pair. When the positron annihilates, two 511-keV photons are formed which scatter in the material and are finally totally absorbed.
4) Same as previous point, but the other 511-keV photon escapes from the detector. In this case, the observed energy is 511 keV less than the energy of the gamma ray hitting the detector.
5) Same as previous point, but now both 511-keV quanta escape. The observed energy is 1022 keV smaller than that of the initial gamma ray.

In addition to these, the gamma ray may also pass through the detector without interacting at all. Probabilities of various processes depend on the energy of the photon, the used detector material and the size of the detector. In Fig. 2 an idealized gamma spectrum is shown.

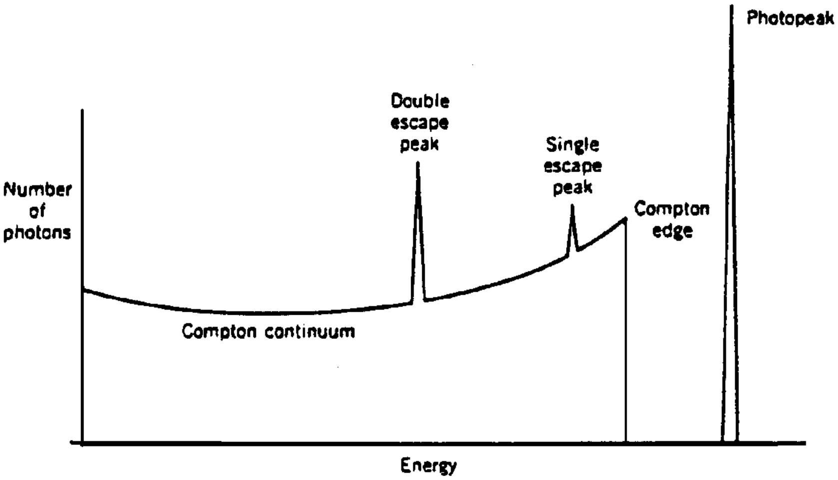


Figure 2. Idealized picture of a gamma-ray spectrum due to a mono-energetic gamma ray. The photo peak represents these cases where the initial energy is fully absorbed (processes 2 and 3). The Compton tail (or continuum) results from the processes where the photon escapes from the detector after a few scatterings (process 1). Escape peaks are due to escapes of annihilation quanta from the detector (processes 4 and 5).

Compton scattering

The process where a photon (γ) scatters from an electron is called Compton scattering. In the scattering a scattered photon (γ') and an electron with kinetic energy of T_e are born.

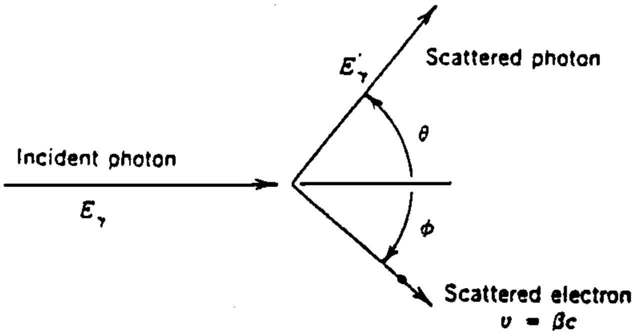


Figure 3. Geometry of Compton scattering

According to relativistic kinematics (derive the results), the energy of the scattered photon depends on the scattering angle as follows:

$$E_{\gamma'} = \frac{E_\gamma}{1 + (E_\gamma / mc^2)(1 - \cos\theta)}, \tag{1}$$

from which the kinetic energy of the scattered electron can be calculated as

$$T_e = E_\gamma - E_{\gamma'} = \frac{E_\gamma{}^2 (1 - \cos\theta)}{mc^2 + E_\gamma (1 - \cos\theta)}.$$

The cosine function gets its minimum value at θ = 180º and there the kinetic energy reaches its minimum value

$$T_{e,\min} = \frac{2E_\gamma{}^2}{mc^2 + 2E_\gamma}.$$

This energy represents the maximum energy of the Compton tail and therefore it determines the position of the Compton edge in the spectrum of figure 1. Interaction processes between radiation and matter are discussed in more detail in Krane, Introductory Nuclear Physics, Ch. 7, pages 192-245.

3. Measurement of a singles gamma-ray spectrum with a scintillation detector

A schematic view of a scintillation detector is shown in Fig. 4. The principle of this kind of detector is based on the use of a scintillation material (NaI, BaF ,…) When a photon enters the detector, a burst of small energy photons results. Typically, the wave lengths of these photons is in the visible region and in principle, they can be seen with bare eyes, if the source of radiation is strong enough. When these photons hit the photo cathode, electrons are released. A photo-multiplier tube increases the amount of these electrons with the help of a dynode chain and high voltage (there is a potential difference between the two neighbouring dynodes and this potential difference accelerates electrons released from the previous dynode). A photomultiplier tube has a minimum voltage below which the tube doesn’t give any signal out. Typically the total accelerating voltage is about 1000 V. Somewhere in the dynode chain the number of electrons gets saturated and at the end of the chain, a strong saturated signal is obtained irrespective of the photon energy. If the energy of the photon is needed, it must be taken from a dynode where the number of electrons is not yet saturated, since the number of electrons reaching the photo cathode is proportional to the energy of the photon. Typically, there are two outputs in the photo multiplier: An output for energy measurement and an output from the last dynode for collecting timing information.

The energy signal from the photo multiplier is usually quite weak; therefore it must be amplified before analyzing it. The amplification takes place in two stages:

1) The signal from the photo multiplier is amplified in a preamplifier (PA) close to the detector.
2) The signal (about 100 mV) from the preamplifier is led to a linear amplifier (LA) where the signal is shaped and amplified so that it is suitable for the analogue-digital converter (ADC). The amplitude of the signal from the LA is typically a few volts.

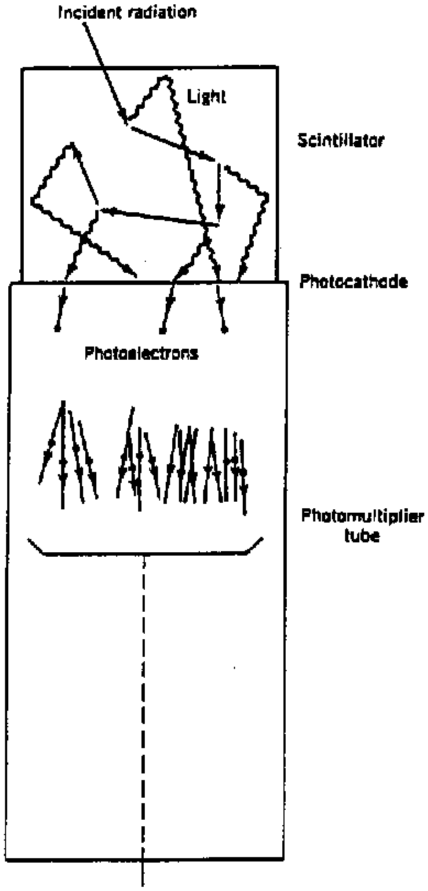


Figure 4. The principle of a scintillation detector

It is useful to view the pulse from the LA with an oscilloscope in order to set the amplification and the rise time (or width of the signal) of the output signal. It is also crucial to adjust pole zero (pz) of the output signal so that the tail of the pulse always reaches the same, zero level irrespective of the signal amplitude. For energy analysis the signal from the LA is taken to a multi-channel analyzer (MCA). A schematic picture of the setup used for measuring the energy of gamma rays is shown in Fig. 5. The MCA is a device consisting of an AD converter and a display. Nowadays, the MCA is usually replaced by a system consisting of a separate analogue-digital converter and a PC loaded with a versatile spectrum-analysis program.

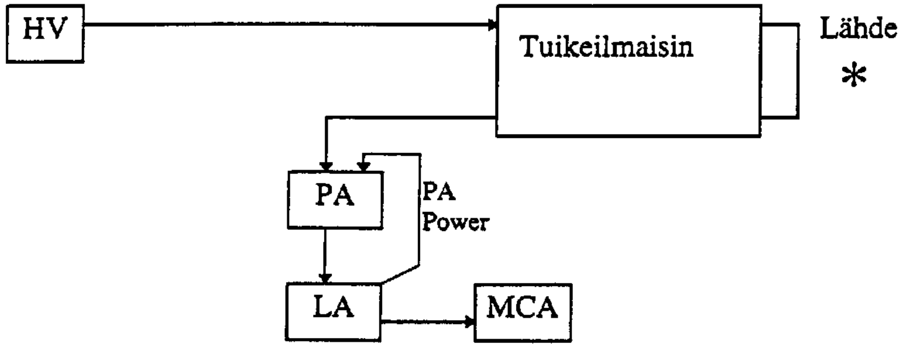


Figure 5. Setup for the energy measurement

After the setup needed in the energy measurement is built and tuned, the following measurements will be done:

1. Measure the energy spectrum for ^{60}Co or ^{207}Bi and determine the energy calibration.
2. Check the accuracy of the energy calibration with the help of another radiation source.
3. Measure the spectrum of ^{137}Cs. Determine the energy of the gamma peak and the resolution of gamma detection.
4. Find the position of the Compton edge in the ^{137}Cd spectrum. Calculate the theoretical energy of the Compton edge and compare it to the experimental value.

Examples of the spectra can be found in appendixes 1 and 2. Principles of photon detection and the handling of amplifiers are explained in the manuals of ORTEC (one of the detector manufacturers).

4. Measurement of a singles gamma-ray spectrum with a Ge detector

The functioning of a Ge detector is based on the use of the depletion region formed between two different (p and n type) semiconductor materials. In normal electronics components this region is small, but in the Ge detector it is made “massive” with the help of reverse bias. The bias is typically 3000-4000 V. The operation of the detector is based on interaction of gamma rays and the semiconductor within this depletion region. When a photon enters the depletion region and interacts there, it excites electrons to the conduction band and electron-hole pairs are formed. The number of electron-hole pairs is directly proportional to the energy absorbed in the material. The charges are collected to the electrodes. As with the scintillation detectors, the pulse obtained in collection of charges is very small. Therefore, the Ge detector is equipped with a preamplifier mounted next to the Ge crystal. A Ge detector can not be operated at room temperature, because thermal electrons mask all weak signals. That’s why the Ge detector is cooled down by liquid nitrogen. A schematic view of the Ge detector is presented in Fig. 6.

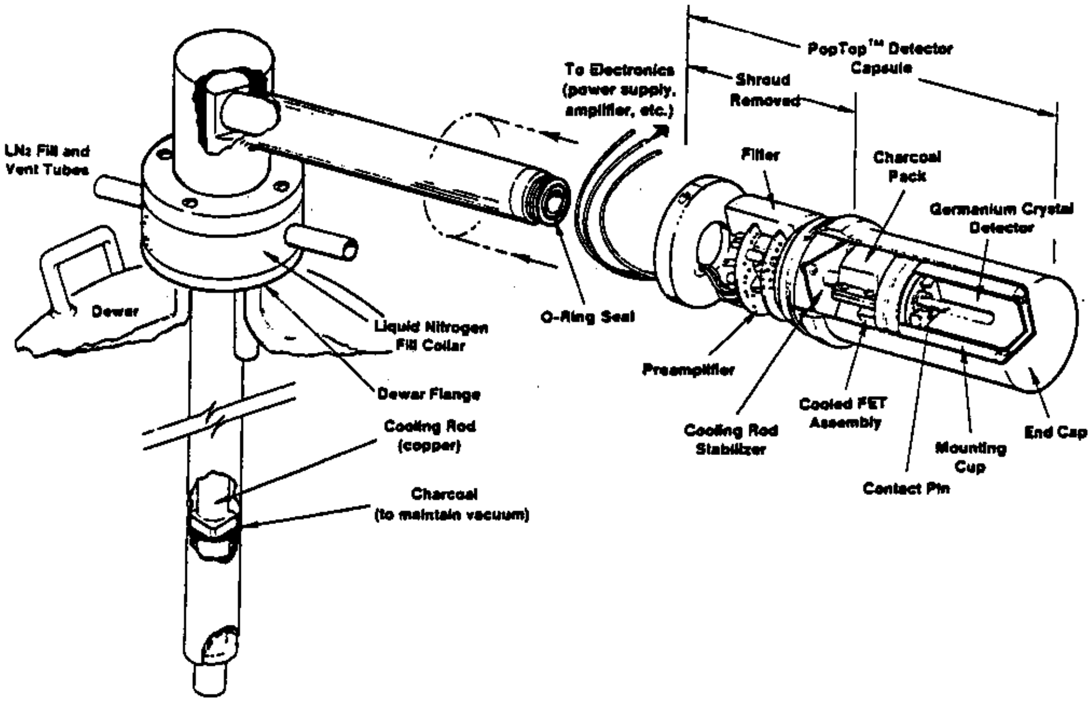


Figure 6. Exploded view of Ge detector

A typical setup for energy measurements is illustrated in Fig. 7. Also shapes of the pulses after the preamplifier and linear amplifier are shown. As in the case of the scintillation detector the amplitude of the pulses after the LA should be a few volts (remember also the pz-adjustment). Pay attention to the polarity of the bias. When biasing the detector, keep the signal connected to an oscilloscope in order to monitor the signal from the PA. You should notice that the noise level of the signal decreases when bias is increased (otherwise there is something wrong with the detector).

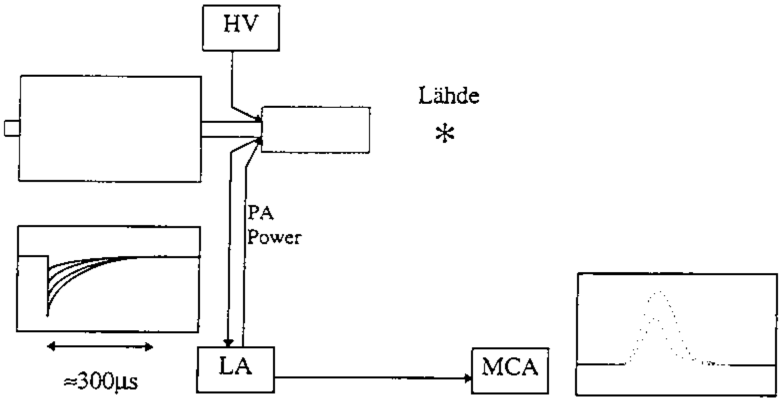


Figure7. Setup for measurement with a Ge detector.

Repeat the same measurements as with the scintillation detector and compare these two different detectors. Appendices 3-5 show typical spectra measured with a Ge detector.

4.1. Absorption of gamma radiation

Absorption of gamma radiation can be studied using a setup similar to that in Fig. 8. In this work absorption of radiation is studied for lead. The principle of measurement is as follows:

a) First measure the gamma-ray spectrum of the ^{207}Bi source (with a distance from the source to the detector of e.g. 10 cm and a measuring time of 10 minutes). Fit the areas of the peaks.

b) Add a lead absorber between the source and the detector and repeat the measurement.

c) Add the second, third, fourth etc. absorber and repeat the measurement.

Plot the area for each peak in the spectrum as a function of the thickness of the absorber material and determine the half thicknesses. Compare your results with those in the book by Juhani Kantele (see appendix 6 of this manual).

Repeat the measurement for the ^{137}Cs source. During each measurement, record the typical counting rate (for example for 10 seconds) from a pulse counter (scaler) for each measurement. Make a plot showing both the number of counts and the peak areas for the peak in the spectra. Compare these to the curves in appendix 6. Why is the result calculated from the counts (from counter) larger than that from the peak areas? What is the meaning of the half thickness? What should be taken into account when protecting against the radiation?

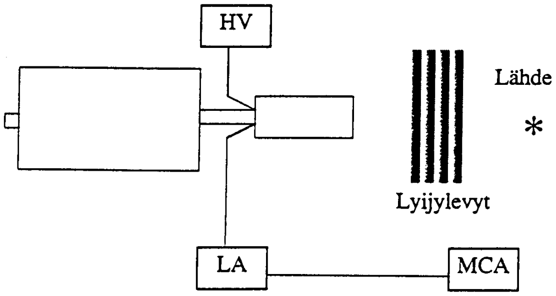


Figure 8. A setup for studying absorption of gamma radiation.

5. Coincidence measurements

Most often, the information available from one detector is not enough for the purposes of nuclear structure study, since the character and ordering of the gamma rays cannot be determined with just one detector. Therefore we need a setup consisting of several detectors. Coincidence principle means that a detection of radiation is accepted (or sometimes rejected) if something is observed “simultaneously” (within 100 ns for example) in some other detector. Coincidences are crucial e.g. in construction of nuclear level schemes. If a nuclear spectroscopist wants to do a really careful measurement, the setup may contain several detectors for observing gamma rays, various charged particles, and neutrons, all operated in coincidence mode.

Simple coincidence setup

The coincidence is done electronically as follows (see Fig. 9):

a) The preamplifier signal is passed from each detector to the Timing filter amplifier (TFA), which is a fast amplifier.

b) The signal from the TFA is passed to the constant fraction discriminator (CFD) which transforms the almost Gaussian pulse from the TFA to a square pulse (in this work 200 ns is suitable for the width of the pulse). The leading edge of the pulse corresponds to the moment when the gamma ray hits the detector. The threshold of the CFD has to be adjusted so that this unit does not trigger from the noise. Adjustment is done connecting the energy signal to the other input of the oscilloscope and triggering this by the signal from the CFD connected to the other input. The CFD is tuned by adjusting the threshold so that the noise is removed from the energy signal shown on the oscilloscope's screen.

c) In the next step, the signals from the CFD units are inspected. In order to have coincidences, the signals from both detectors should come at the same time; if not, use a delay box to delay the faster signal.

d) Signals from the CFD units (after a possible delay) are passed to a coincidence unit. An output is given when there is an input signal present in two input channels. If the other input signal is connected to the veto input, an output is obtained only if the signals were on simultaneous (i.e. they don't overlap). This is called anticoincidence.

e) Finally, the timing of the energy signal and the coincidence signal have to be set in a certain way. The final selection of the energy signal is done in the AD converter which is most often operated in the so called delayed mode. This means that the coincidence signal has to be delayed (GDG (gate and delay generator) in Fig. 9) to coincide with the trailing edge of the energy signal.

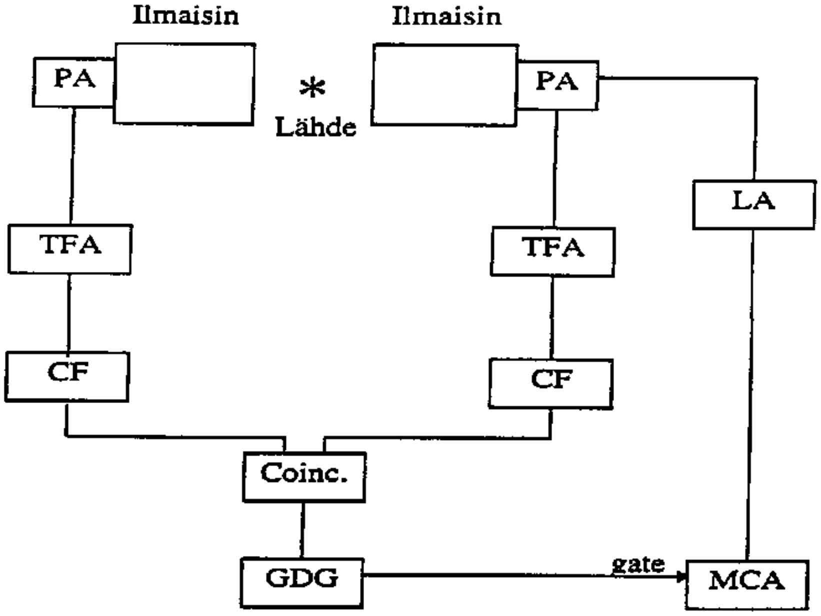


Figure 9. A simple coincidence setup of two detectors

6. Escape- suppression shield

The Compton tail present in the spectrum measured with a Ge detector can be removed to a large extent, if events involving a photon escaping from the detector crystal are removed. This can be achieved, if a shield capable to detect the escaping gamma rays and the anticoincidence mode are used. The structure of the escape-suppression shield (also called anti-Compton shield ACS) is shown in Fig. 10. It is made of an effective scintillation material like BGO or NaI (or both) surrounding the Ge crystal. A block diagram of the electronics used is shown in Fig. 11.

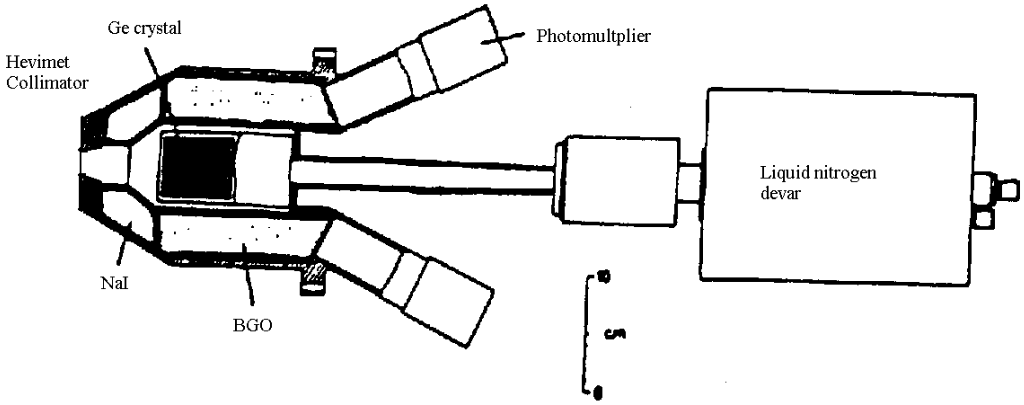


Figure 10. The escape-suppression shield

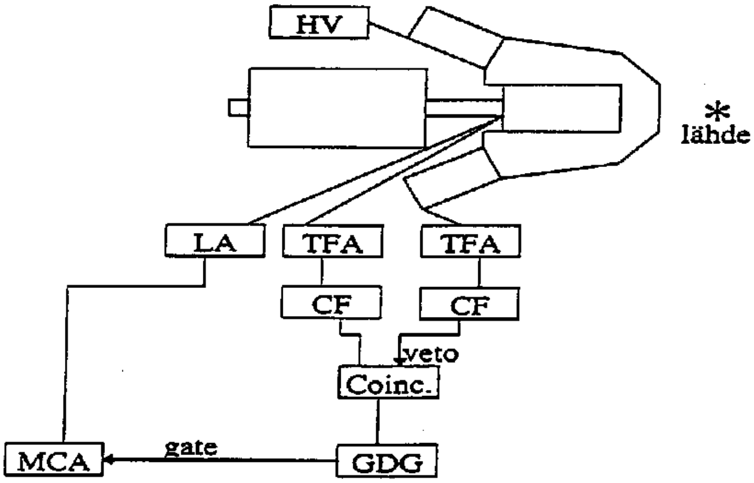


Figure 11. Block diagram of electronics utilizing an ACS

Measurements with ACS

Built the setup for the anticoincidence measurement and measure the following spectra:

a) Measure the gamma-ray spectrum of a ^{137}Cs source without and with the ACS. The source should be directly in front of the shield at a distance of about 20 cm from the Ge detector. Why is this important? From both spectra measured, determine the peak/total ratio. How large is the portion removed from the Compton background when using the ACS?

b) Change the anticoincidence to coincidence and measure the spectrum of rejected events.

Examples of spectra can be found in appendices 7 and 8.

7. More complicated coincidence setup; use of an energy window

The coincidence setup presented earlier was quite simple, since only a timing condition was set. More information of an event is gained if also an energy condition is required. When inspecting the pulses caused by the ^{22}Na source with the oscilloscope pulses with different amplitudes are seen. One amplitude is present more often than the other amplitudes, corresponding to the 511-keV peak in the gamma-ray spectrum. With help of a single-channel analyzer (SCA) one can select pulses having a certain amplitude from the spectrum. This is called “gating”.

Tuning of the SCA module

a) Inspect the bi-polar signals from the linear amplifier with the oscilloscope.
b) Pass the uni-polar signal of the LA to the input of the SCA and use the output of the SCA to trigger the bi-polar signal in the oscilloscope.
c) Set E and ΔE so that only the desired pulse heights are accepted.

Measurements using two scintillation detectors

The block diagram for a measurement utilizing two scintillation detectors and an energy window provided by the SCA is shown in Fig. 12. Using this kind of setup and two BGO detectors, demonstrate that the annihilation quanta have a certain angular dependence.

a) Place the detectors face-to-face at about 10 cm from each other.
b) Put a ^{22}Na source in the middle.
c) Set the SCA to accept 511-keV (about!) peaks and use the output of the SCA to gate the ADC.
d) Measure the spectrum.
e) Change the angle of the other detector so that the detectors are no more face-to-face and repeat the measurement.

This setup can be used to observe cosmic muons, as well.

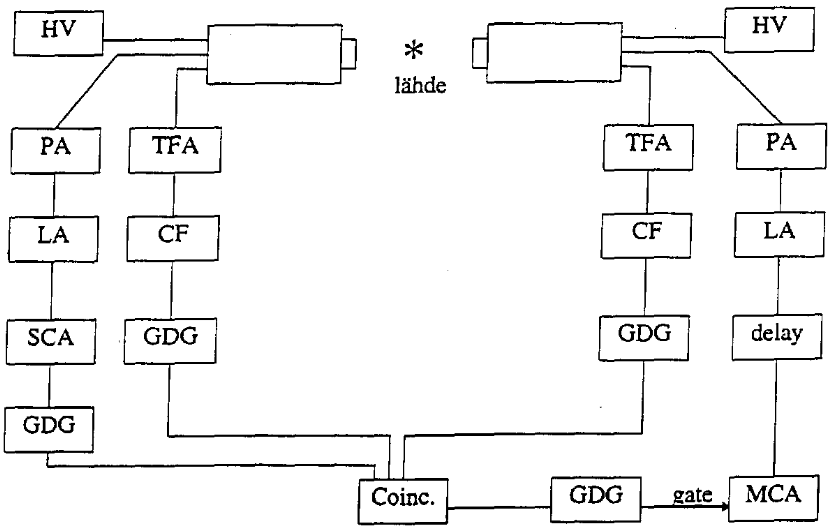


Figure 12. Coincidence setup involving the energy gate

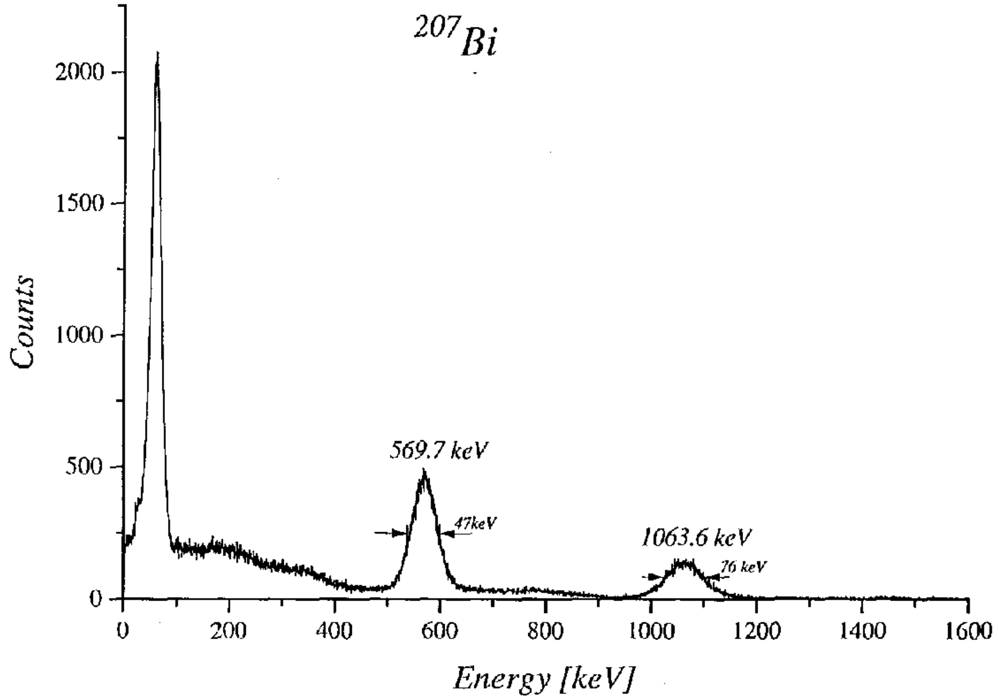
Measurements with two Ge detectors

The same setup can be used with Ge detectors as well. To demonstrate this, do the measurement using the ^{207}Bi source. The gamma-ray spectrum of the ^{207}Bi source has three peaks.

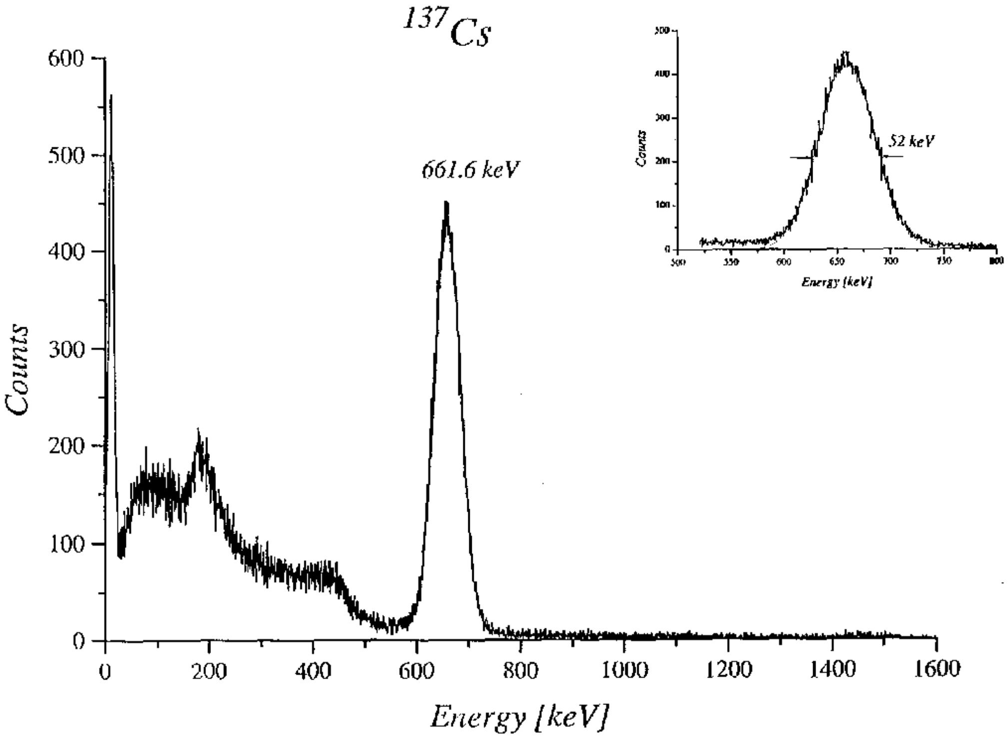
a) Set the gate signal on one of these gamma rays and measure the spectrum.
b) Repeat the measurement with the gate set on the other two peaks and measure the spectrum in each case.

Determine the ordering of these gamma-ray transitions based on your spectra and construct the level scheme. Why should the peak corresponding to the gate signal disappear from the spectrum? Does it disappear completely? Why? Do the spectra define the level scheme uniquely?

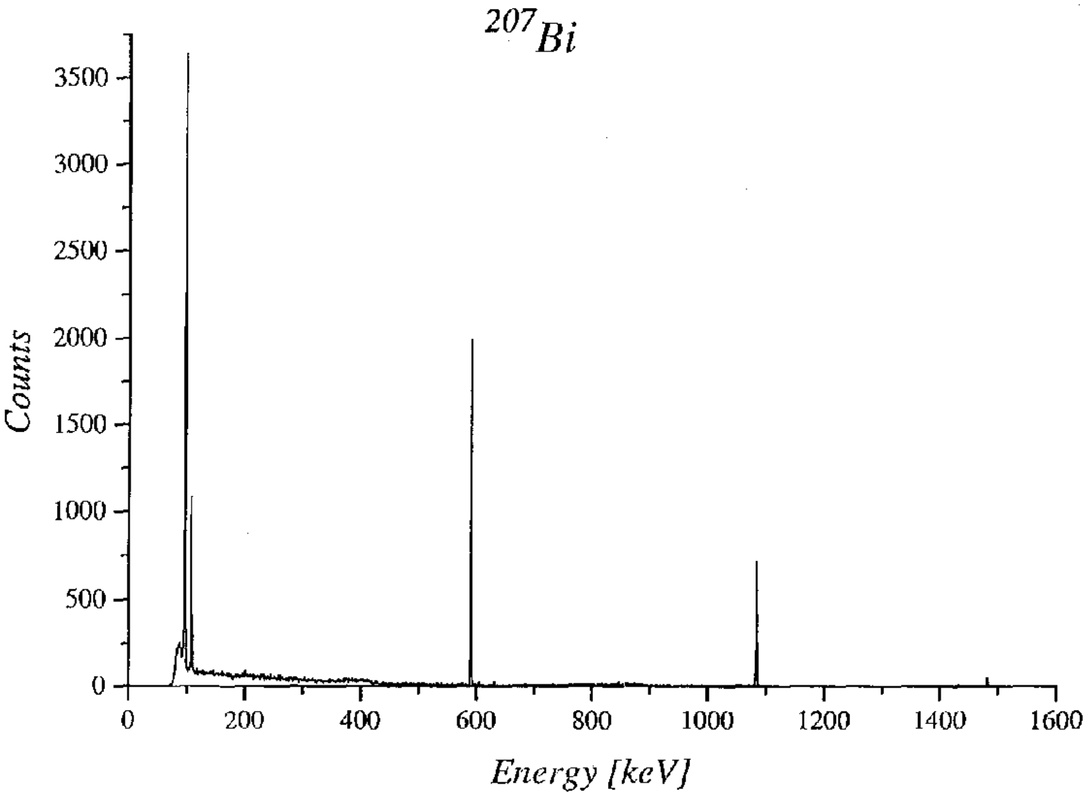
Appendix 1. The gamma-ray spectrum of ^{207}Bi as measured with a scintillation detector.



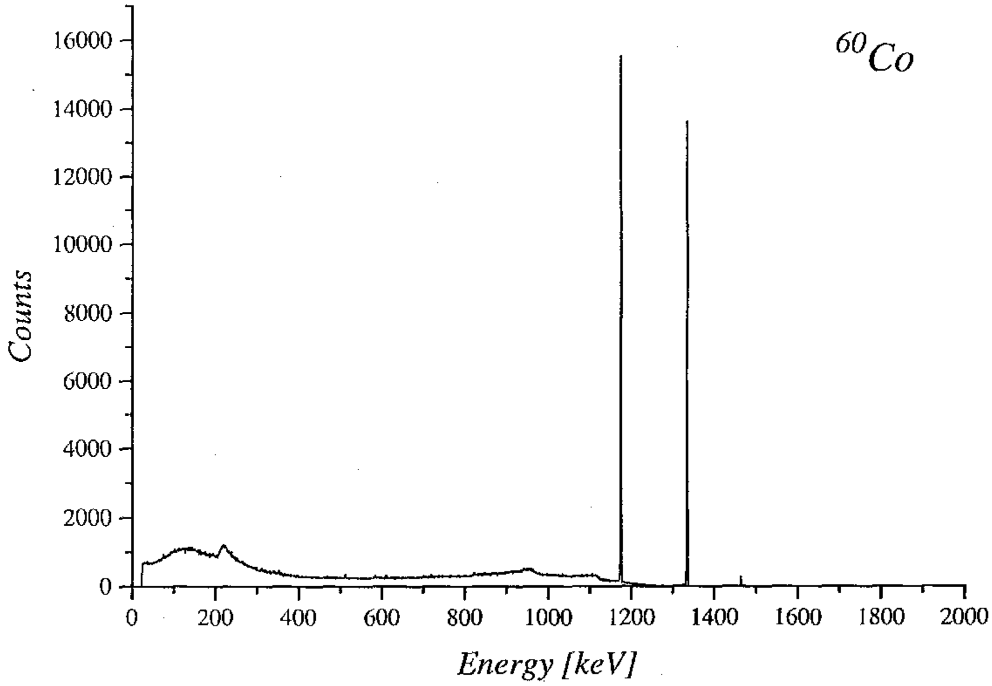
Appendix 2. The gamma-ray spectrum of ^{137}Cs as measured with a scintillation detector



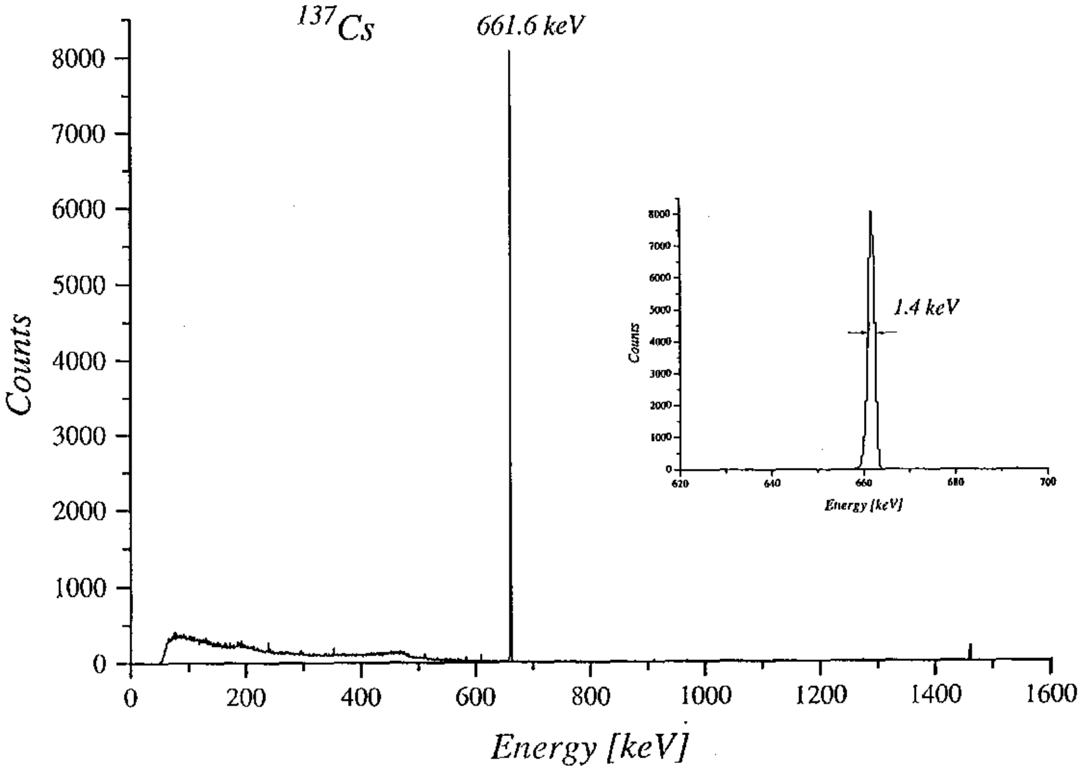
Appendix 3. The gamma-ray spectrum of ^{207}Bi as measured with a Ge detector



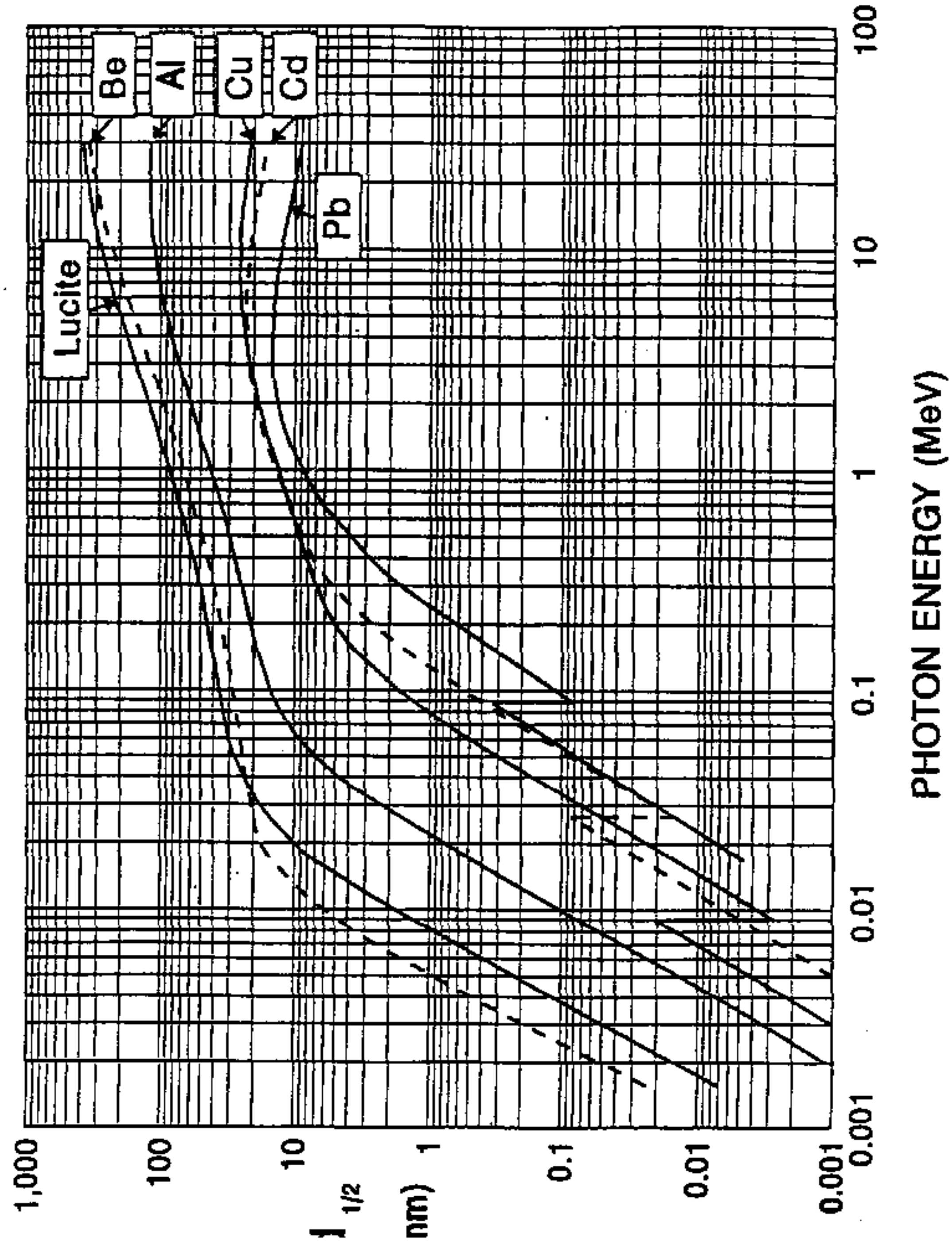
Appendix 4. The gamma-ray spectrum of ^{60}Co as measured with a Ge detector



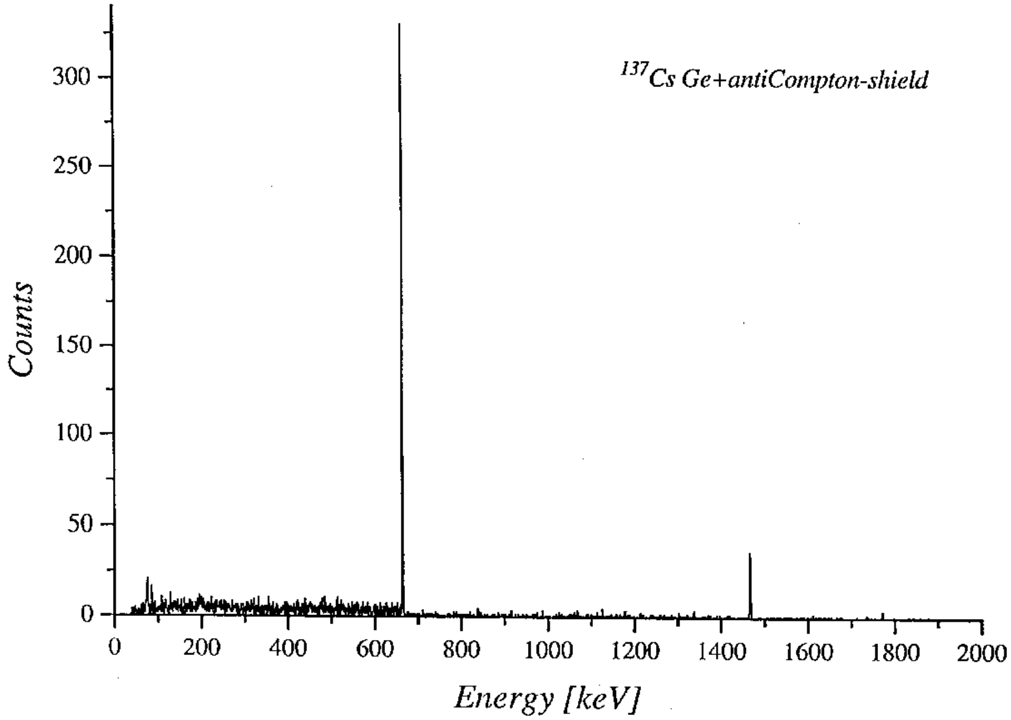
Appendix 5. The gamma-ray spectrum of ^{137}Cs as measured with a Ge detector



Appendix 6. Half-thickness curves of gamma radiation for various absorber materials



Appendix 7. The gamma-ray spectrum of ^{137}Cs source; photons escaping from the Ge crystal vetoed with ACS



Appendix 8. The spectrum of vetoed gamma-ray from ^{137}Cs source