GAMMA-RAY SPECTROSCOPY

LATEST VERSION: 14/02/2025

AUTHOR: ANDREO CRNJAC, NÚRIA CASACUBERTA AROLA, CHRISTOF VOCKENHUBER

Abstract: In this experiment you will learn how to measure radiation from gamma-emitting nuclei. To detect gamma rays, two different detectors will be used, a sodium iodide scintillator and a germanium semiconductor detector. The operating principles of both devices will be studied, and their detection efficiency and energy resolution will be compared. You will use the gained knowledge to identify the isotopic content and activity of the radiation sources.

NOTE: During the experiment, the student will work with radioactive sources. The sources must be stored in the container immediately after the measurement. If anything is unclear please notify the assistant or laboratory technician.

Physics Lab

ETH zürich

https://vp.phys.ethz.ch/

Table of Contents

1 Preparation for the experiment

1.1 Interaction of electromagnetic radiation with matter

Gamma rays, also known as gamma radiation, refer to high-energy photons usually produced during the decay of the atomic nucleus. Due to the particle-wave nature of photons, the energy they transfer can best be described by the electromagnetic frequency υ, and $E = h\upsilon$, where h is the Planck constant. Other common sources of electromagnetic radiation are listed in Figure 1. In this experiment, the student will use prepared gamma sources containing unstable nuclei and observe the properties of emitted photons by their interaction with radiation detectors. Gamma photons will transfer their energy to the detector via these interactions, and the student will observe the spectrum of recorded energies. Photons do not have rest mass or charge; therefore, their interaction with material is different from the energy loss of heavy (ions) or light (electrons) charged particles. The main interaction mechanisms of gamma rays with matter are: photoelectric effect, Compton scattering and pair production. These processes lead to the partial or complete transfer of energy carried by the gamma-ray photon to the electrons and atoms of the absorbing medium. Here we will describe the basic principles of the 3 interaction mechanisms, more details can be found in [5, Chapter 2.7].

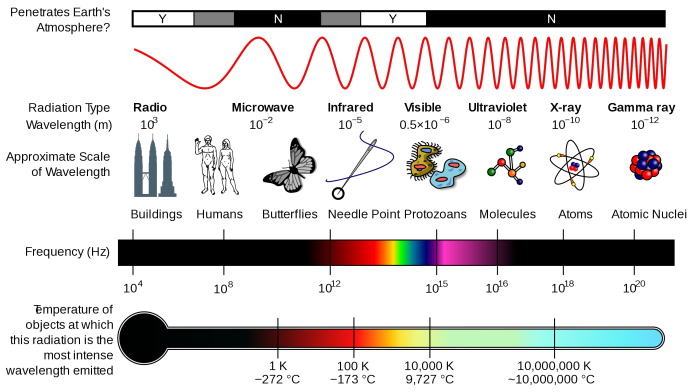

Figure 1: Electromagnetic spectrum. Source: Wikipedia

1.1.1 Photoelectric absorption

Photoelectric absorption is an interaction in which the incident gamma photon is absorbed by an atomic electron, and the electron (photoelectron) is emitted from one of the electron shells of the target atom (absorber), with a kinetic energy given by the incident photon energy hυ minus the binding energy of the electron (E_b).

$$T = h\upsilon - E_b \tag{1}$$

The electrons will only be able to absorb energy from the photon if its kinetic energy is greater than the electron binding energy. K-shell electrons have the highest binding energy, followed by L-shell and M-shell electrons. Interaction on other shells is not likely for gamma-ray energies. The photoelectric absorption is a common process in gamma-ray spectroscopy. Once the photoelectrons have been produced, if they don't escape from the detector, then the sum of the

kinetic energies of the electrons that are created must equal the original energy of the incident photon (Figure 3).

1.1.2 Compton scattering

The Compton scattering is an interaction process that takes place between the incident gamma photon and an electron in the absorbing material. The incoming gamma photon is deflected through an angle θ with respect to its original direction. Scattering is only probable if the photon energy is much higher than the electron binding energy, so that it can essentially be approximated as free. The photon transfers a portion of its energy to the electron which is recoiled from the atom (Figure 2) and detected by the detector. The expression that relates the energy transfer

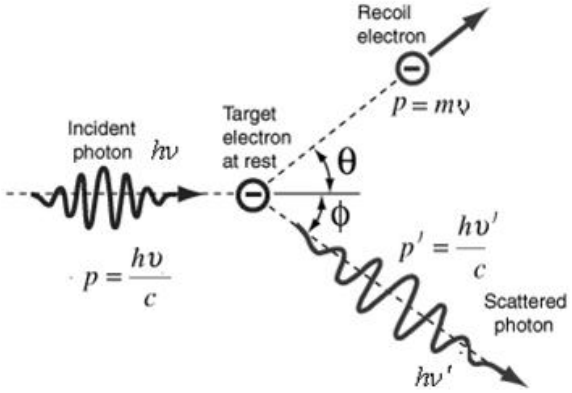

Figure 2: Kinematics of of Compton scattering. Source: [4]

and the scattering angle for any given interaction can simply be derived by writing simultaneous equations for the conservation of energy and momentum. The energy of the scattered photon can be calculated using the following relation:

$$h\upsilon' = \frac{h\upsilon}{1 + \frac{h\upsilon}{m_0 c^2}(1 - \cos\theta)}, \tag{2}$$

where $m_0 c^2$ equals the rest-mass energy of the electron (0.511 MeV). When the Compton scattering occurs, a continuum of energies can be transferred to the electron, ranging from zero to the maximum transfer of energy (i.e. when θ equals 0). This continuum of energies is observed in a spectrum and is known as the Compton continuum, with an abrupt drop at the Compton edge (Figure 3).

1.1.3 Pair production

The pair production is a process during which a photon is transformed into an electron-positron (e^- and e^+) pair. Positron is an antielectron, having the same mass but a positive charge. Transformation occurs when the energy of a photon exceeds twice the rest-mass energy of an electron (1.02 MeV). All excess energy carried by the photon is converted into kinetic energy shared by the positron and the electron.

$$E_{e^-} + E_{e^+} = h\upsilon - 2m_0 e^2 \tag{3}$$

Subsequently, the positron is likely to annihilate with an electron in the absorbing medium, and two annihilation photons are produced as secondary products of the initial interaction. Annihilation photons can only have an energy of $m_0 c^2 = 0.511$ MeV each, meaning that during the

annihilation only the energy contained in the electron-positron rest masses is converted to photons. For typical energies of gamma photons, both the electron and the positron travel a few millimetres before losing all kinetic energy to the absorbing medium. At that point, the positron will annihilate. In a detector, the annihilation photons may either escape or undergo further interactions within the detector material. If one annihilation photon escapes without interaction, it is observed in the gamma detector as a peak (single escape peak) that corresponds to the energy of the incident photon minus the 0.511 MeV. The absorption and escape processes in a detector are shown schematically in Figure 3-(a). If both annihilation photons escape, then a second peak (double escape peak) is observed. Figure 3-(b) shows a typical gamma spectrum collected by the gamma detector.

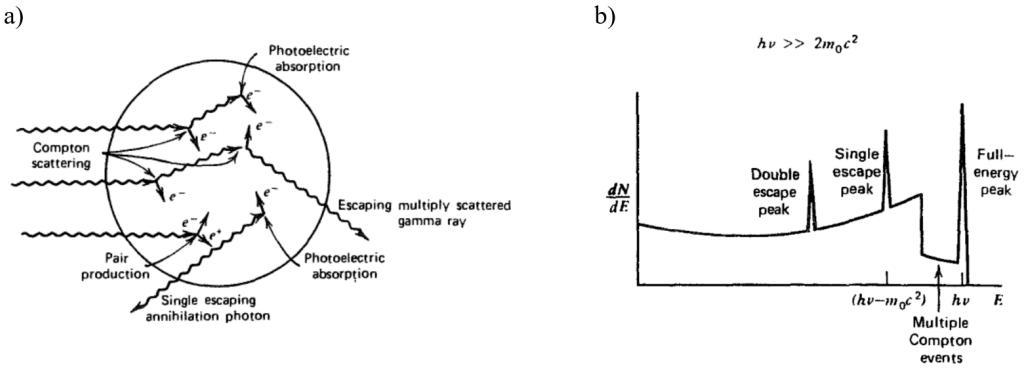

Figure 3: a) Schematic representation of interaction processes of gamma photons in the detector volume that can lead to full absorption of photon energy, or partial escape via scattered gamma photons or annihilation photons. b) Typical count-energy spectrum of a radionuclide emitting gamma photons of a high single energy. The spectrum shows the photo-peak (or full-energy peak), corresponding to the energy of the characteristic gamma line of the radionuclide. By Compton scattering electrons with a wide energy distribution are produced (Compton continuum). By pair production and subsequent annihilation of the positron–electron pairs a peak of 0.511 MeV (annihilation peak) is produced. If the gamma photons of 0.511 MeV escape from the detector without interaction a single and double escape peak appear in the spectrum. Source: [4]

The relative importance of the three interaction processes that depend on the energy of the incident photon are summarised in Figure 4. The total interaction probability for a photon propagating in matter is the sum of the individual interaction probabilities associated with the photoelectric, Compton and pair production interaction mechanisms. Overall, the interaction of any photon will lead to its absorption or scattering from the original impact trajectory. Therefore, a beam of photons penetrating a material will get attenuated in intensity with depth, meaning that fewer photons will reach deeper. Nevertheless, those photons will have the same energy as upon the start of the interaction. Attenuation properties of absorbing materials are typically expressed in terms of the mass attenuation coefficient μ/ρ (cm^2/g), corresponding to the ratio between the linear attenuation coefficient μ, which is independent of material density and slightly dependent on its chemical composition, and the material density ρ. It has been shown that, for gamma photons, the intensity degrades exponentially with depth:

$$I(d) = I_0 \exp(-\mu d), \tag{4}$$

where I_0 is the incident intensity, d is the penetration depth, μ is a linear attenuation coefficient and $I(d)$ is a depth distribution of photon intensity.
From the graph of the mass attenuation coefficient as a function of the photon energy (Figure 4) it is shown that the photoelectric effect, Compton scattering and pair production are the dominant interaction mechanisms, respectively, at low ($E_\gamma < 0.1$ MeV), medium ($0.1 < E_\gamma < 10$ MeV) and high ($E_\gamma > 10$ MeV) gamma energies.

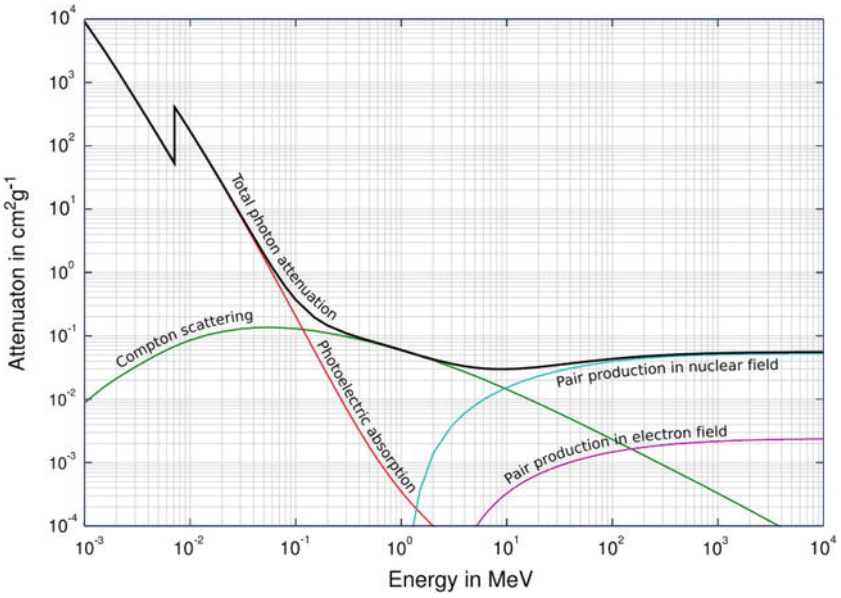

Figure 4: Relative contributions of 3 dominant interaction mechanisms occurring in materials following the absorption of gamma-ray photons. These contributions differ considerably for different absorption materials, driven by the changes in their electronic structure. Note that the attenuation coefficient is normally given in cm^2g^{-1} and thus incorporates the density of the absorbing matter.

1.2 Detectors used in the experiment

1.2.1 Scintillation detector: NaI(Tl)

The detection of ionizing radiation by the scintillation light produced in certain materials is one of the oldest techniques on record [3]. There are various types of scintillation detectors, but this section will cover the thallium-doped sodium iodide detectors (NaI(Tl)), which are the ones used in this exercise. The NaI(Tl) is an inorganic scintillator with exceptionally high light yield. This detector responds to the gamma photon by scintillation - the conversion of energy to visible light photons (see Figure 5). Gamma photons interact with the scintillator material and transfer energy to the electrons which are promoted to the excited electronic states. Scintillation occurs when the electrons return to their ground state and release excess energy as low-energy photons (light). These photons travel freely through the material as their energy is too low to again excite the electron states (in other words the material is transparent for photons of that wavelength). The low-energy photons emitted by the scintillator strike the photocathode glued to one end of the scintillator, where a primary electron (photoelectron) is ejected from the surface as a consequence of the photoelectric effect. This electron is directed by the focusing electrode toward the photomultiplier where secondary electrons are generated (Figure 5). The electron multiplier

consists of a number of electrodes called dynodes. Each dynode is held at a more positive potential, by $\approx 100V$, than the preceding one. The shape and distribution of dynodes create an electric field that guides electrons towards the next-stage dynode. Upon striking the first dynode, more low-energy electrons are emitted, and these electrons are in turn accelerated toward the second dynode. Typically, for each impinging electron, 5 new ones are emitted. At the last stage, for each primary electron, one expects a total accumulation of about 10^8 electrons. The last dynode, called the anode, is also the output of the detector system to signal processing electronics. This large number of electrons reaching the anode results in a sharp current pulse that is easily detectable, for example on an oscilloscope, signalling the arrival of the photon(s) at the photocathode ≈ 50 nanoseconds earlier.

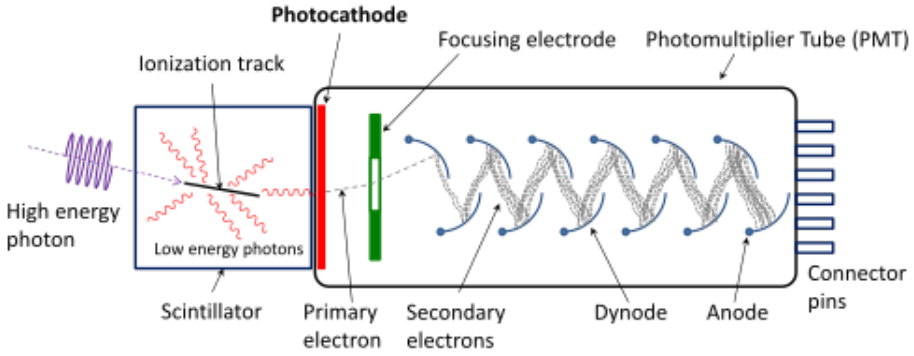

Figure 5: Schematic of a photomultiplier tube coupled to a scintillator. Source: Wikipedia

The most notable property of NaI(Tl) is its excellent light yield, which normally results in higher detection efficiencies compared to other gamma-ray detectors. Yet, the crystal is somewhat fragile as it is hygroscopic and will deteriorate due to water absorption if exposed to the atmosphere for a longer time. Crystals must therefore be encased in a moisture-protective casing, which also serves as a convenient mounting for the entire crystal/photomultiplier unit. One of the major limitations of scintillation counters is their relatively poor energy resolution. The chain of events that must take place in converting the incident radiation energy to light and the subsequent generation of an electrical signal involves many inefficient steps. The energy resolution for sodium iodide scintillators is limited to about 6% when detecting 0.662 MeV gamma rays and is largely determined by the statistical fluctuations occurring during signal generation in the detector.

1.2.2 Semiconductor detector: high-purity Germanium

To understand the principle of operation of solid-state semiconductor detectors, we first need to introduce the concept of band energy structure. In crystalline materials, electrons can be bound to the atoms in the crystal lattice or free to move around. It can be demonstrated that the periodic lattice of crystalline material establishes allowed energy states in which electrons can exist. These states are grouped into two bands, the valence band (bounded immobile electrons) and the conduction band (free mobile electrons). The second band is called conduction, as the free-moving electrons are those responsible for the electrical conductivity of the material. In between these states there exists a region of forbidden energy states in which electrons can not exist, a forbidden energy gap. For an electron to become mobile, it needs to gain energy higher than the band-gap energy, and be promoted to the conduction band. This energy, E_{gap}, is expressed in units of eV, or electron-Volts. The size of the forbidden energy gap determines if the

material is classified as an insulator, semiconductor or conductor (metal), as shown in Figure 6. In metals, the valence and the conduction band overlap, which results in some electrons always

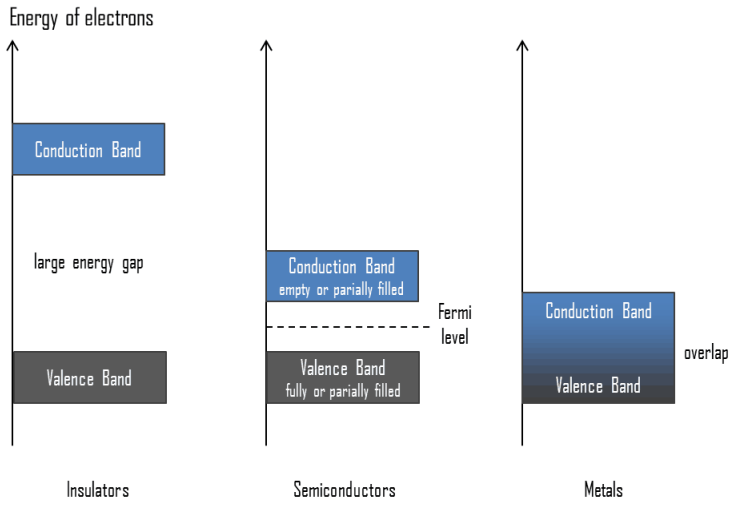

Figure 6: Band structure for electron energies in insulators, semiconductors and metals

occupying conduction states. In the presence of the band-gap, electrons can become conductive only due to thermal excitations or due to the presence of other processes that result in a transfer of energy to the electrons. The interaction of gamma rays with semiconductor crystal is an example of such a process which will generate free electrons. This principle is successfully employed to construct semiconductor gamma detectors, in which a sensitive volume made out of semiconductor medium is exposed to radiation, and created free electrons are collected by electrodes placed on the opposing edges of the sensitive element. In semiconductor theory, it is often useful to envision that the electron being excited to the conduction band leaves behind a positively charged lattice atom space, called a hole (due to a missing electron). Holes can be seen as equally important charge carriers as electrons, and the process of charge collection in the sensitive volume should be seen as a collection of both electrons and holes. The most used semiconductor materials in radiation detection are silicon (E_{gap} = 1.12 eV) and germanium (E_{gap} = 0.67 eV). As an example, the total absorption of a 1 MeV photon produces around 3×10^5 electron-hole pairs in germanium. Since germanium can have a depleted sensitive thickness on the order of centimetres, they are able to fully absorb high-energy photons (up to a few MeV in energy). The number of electron-hole pairs is proportional to the energy of the radiation deposited in the semiconductor, therefore the height of the collected signal can be used to measure gamma energy. High-purity germanium crystal, free of lattice defects, is used to ensure good electrical properties required in applications such as gamma detection. One disadvantage of germanium-based detectors is that they have such a low forbidden energy gap that at room temperature, thermal excitations are strong enough to constantly promote free electrons, which would disable their operation as detectors. To suppress thermal events, active cooling to cryogenic temperatures is required. The cooling is typically accomplished using a liquid cryogen, most commonly liquid nitrogen (LN_2), or with an electromechanical cooler, as is the case with the detector used in this experiment.

The important advantage of germanium solid-state detectors over scintillators is in the more efficient energy transfer from gamma photons to the sensing material. This results in higher detection efficiency, which in practical terms also ensures higher energy resolution.

More details on the principles of semiconductor radiation detectors can be found in [4, Ch. 11 & 12].

2 Experimental setup

2.1 Samples

A set of radiation-emitting samples/standards will be used for this experiment - information about them is summarized in Table 1. Additional and more specific information about the half-lives, emission lines an probabilities of each radioisotope can be found in the appendix B and other references [2]. During data collection samples are fixed in the sample holders of the detectors, afterwards they must be stored in the holding containers.

Sample number	Isotope/s	Activity (Bq)	Date of calibration
1	^{207}Bi	tbd	na
2	^{60}Co	tbd	na
3	^{60}Co	tbd	na
4	^{22}Na	tbd	na
5	^{152}Eu	37×10^3	January 1996
6	^{137}Cs	42×10^3	January 2000
7	^{137}Cs	tbd	na
8	Unknown	tbd	na
9	Unknown	tbd	na

Table 1: List of standards used in this experiment. The acronym "tbd" stands for "to be determined" and "na" for "non applicable".

2.2 Detector operation

There are two types of detectors available for students to perform this experiment, a scintillator thallium-doped sodium iodide detector and a semiconductor high-pure germanium detector.
The scintillator used in this experiment is a NaI(Tl) coupled to a photomultiplier. Students should perform the measurements by applying a voltage of 1 kV and a current of up to 2.5 mA to a photomultiplier. ***Apply the voltage slowly!*** The source is placed in the lead container, at a distance of 35 mm from the detector.
The semiconductor detector used for this experiment is a commercial solution from Mirion Technologies (Canberra). Because germanium has a relatively low band gap, the semiconductor must be cooled to reduce the thermal generation of charge carriers (leakage current) to an acceptable level. Otherwise, leakage current induced noise degrades the energy resolution of the detector. The Cryo-Pulse 5 Plus cryostat is an electrically powered cryostat for use with HPGe radiation detector in this experiment. It consists of a cold head assembly, to which the detector is attached, and an external power controller.
Furthermore, an electric field must be established across the semiconductor volume through

the electrodes. This field is used to collect created electrons and holes. Charge signal is extracted from the electrodes and further amplified by the electronics, so that it can be properly observed on the oscilloscope or stored digitally. Students should perform the measurements with an applied voltage of 4 kV across the electrodes. ***Apply the voltage slowly!***
The sample holder for a semiconductor detector setup can be placed at different distances from the crystal, which changes the sample-detector solid angle. The student should choose one position of the sample holder and measure all the samples without further changes in the geometry.

2.3 Computer program MCA-3

Students will collect output signals from the detectors using the supplied data acquisition software MCA-3. Here is a short overview of the operating procedure for the software.

- Switch on the PC and start the program MCA-3.
- With the symbol "play" you can start/stop the measurement.
- For the energy calibration, click the "Calibration" button and enter the different energies corresponding to each peak. The best way to do it is to put the cursor on top of the peak and associate the energy corresponding to this.
- To quantify the peaks, a Region of Interest (ROI) can be used by right-clicking and drawing the ROI around the peak area with the mouse; then select the "Create new ROI" option from the upper toolbar.
- To fit the peaks into a Gaussian, click on the "Gaussian Fit" button.
- You can save the spectra as ASCII or txt files. For each of the 8192 channels, the recorded number of counts is saved, and this is displayed in a two-column format.
- Be careful not to overwrite previous data files when starting a new measurement - save a new file before the measurement start, and save again to that file after stopping the data collection (more instructions given by the assistant).

2.4 Gamma spectra collection

The main experimental work in this exercise consists of the successful collection of gamma spectra produced by samples containing known gamma-emitting nuclei as well as unknown nuclei. The gamma detector is exposed to the radioactive sample and the output of the detector is collected by the data acquisition system. Each gamma impinging on the detector will produce a measurable signal, which is stored by the software. The system for signal processing between the detector and the acquisition system is quite complex, but the basic scheme of the processing electronics is given in Figure 7-(a). A more detailed overview of signal processing in gamma-spectroscopy experiments can be found in [6]. The charge created by the radiation in the detector is processed by the charge-sensitive amplifier and converted to a voltage pulse signal. The amplifier is linear, meaning that the pulse height is proportional to the accumulated charge, which is proportional to the deposited energy of the gamma photon. The signal is further sent to the ADC (Analog to Digital) and MCA (Multi-Channel Analyzer) where the pulse-height is analyzed and the analogue signal is converted to digital pulse so that the data-acquisition software

can store the events in different channels according to pulse height. Events are accumulated on the counts-channel plot, which can be called the gamma spectrum. Calibration of channel number to radiation energy is performed so that the calibrated data are represented in counts-energy units, which are more meaningful in data analysis. A typical result of the data collection with a scintillator and germanium detector for one of the samples is shown in Figure 7-(b).

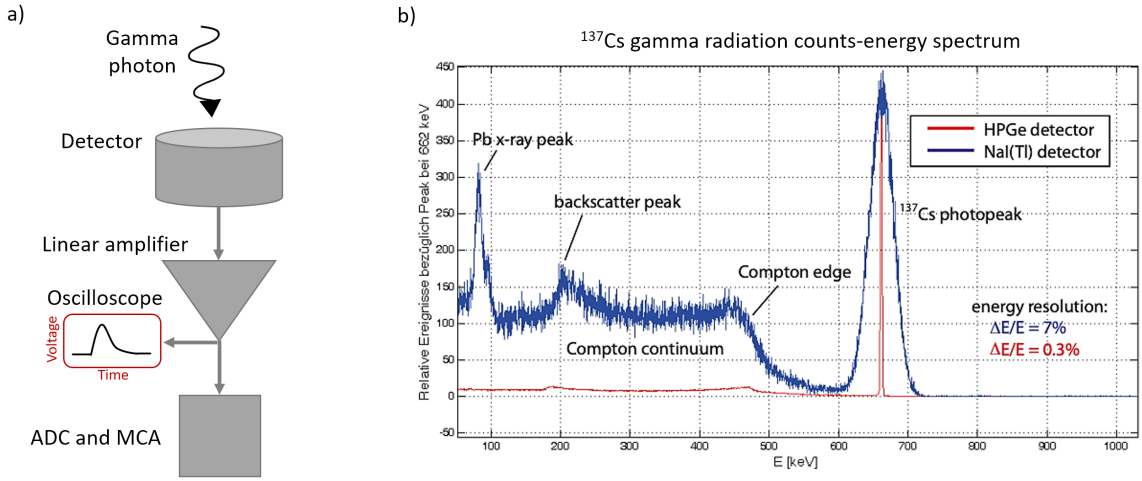

Figure 7: a) Basic schematics of the signal processing electronics used in gamma-ray spectroscopy. b) Counts-energy spectrum collected from ^{137}Cs source.

It can be seen that the two spectra are different, due to the different sensitivity of the detectors, as well as due to the different detector geometries. Namely, in the energy spectrum collected by the scintillator, additional low energy peaks, X-ray and backscattered events, are detected, which are a result of the interaction of photons with the detector shield. More information about these processes will be given during the performance of the experiment by the assistant.

3 Aim of the experiment

The aim of the gamma-ray spectroscopy experiment is to compare the two gamma detectors in terms of their performance and acquire the skills to use gamma-ray detectors to identify and quantify the radioactivity of environmental samples.
The successful implementation of the experiments will require the use of the following principles and skills:

- Basics of radiation activity units and radiation protection (see Appendix A)
- Structure of atomic nuclei and the generation of radiation, especially the mechanisms of gamma-radiation. Students are encouraged to read relevant nuclear physics literature [3, Chapter 1]
- The interaction processes of gamma-radiation with matter.
- Operating principle of detectors that are used to measure gamma radiation, as well as basic principles of signal processing - linear amplifier, multi-channel analyzer.
- Operation of the data acquisition tool, particularly fitting of Gaussian functions to data.

- Procedure for the identification of gamma-emitters and for the absolute determination of the activity of an investigated radioactive source

Carrying out the experiment requires intensive preparation by the student. This manual is intended as a guide for the preparation of the experiment. However, it cannot give a complete introduction to all questions. For this reason, the student should also use the literature given at the references section.
Students will get initial instructions and help from the experiment assistant. *Do not operate the detectors on your own before receiving these instructions.* During the experimental work, the students should keep notes on the procedures and observations they made. These notes are used to help them refresh their memory during the data analysis and report writing.

4 Results and Discussion

4.1 Estimation of the source activity using rate-meter

The student lab is equipped with a radiation rate-meter which can be used to estimate the number of gamma rays emitted towards a certain solid angle covered by the rate-meter. *Measure the dose rate* of a ^{137}Cs source as a function of distance (without the lead shielding). *Fit the data with an appropriate function.* Take into account the background activity. Assess the radiation exposure from this radioactive source for the duration of your experimental work in the lab.

4.2 Main experiment execution

To understand the process of radiation detection, the output of the signal processing electronics should be inspected on the oscilloscope to observe the properties such as peak structure, background noise, and signal-to-noise ratio. The amplifier unit has a variable gain which can be adjusted so that the maximal detected peak height fits in the range of accepted values for analogue to digital conversion (0-10V). The signal collection is also affected by the settings of the power supply units of the photomultiplier (for the scintillation detector) or the HPGe detector. Consult with the assistant to better understand what values to use, and what are maximum safe operating power supply voltages. Students should also acquire background spectra with both detectors, and identify what gamma energies are present in the atmosphere. This information should be used when measuring gamma spectra from the source - *identify background peaks and disregard them.*

4.3 Energy calibration

Energy calibration means evaluating a relationship between the energy of the emitted particle and the channel number of the event stored by the data acquisition system. Start with the ^{137}Cs sample, as there is only one photopeak (662 keV) and therefore is easier to identify in the counts-channel spectrum. Assume that channel 0 corresponds to 0 energy. Use these two points for a first channel-energy calibration. Next, use ^{152}Eu source (identify as many peaks in the spectrum as possible: 122, 245, 344, 778, 964, 1112, 1408 keV) and improve on the calibration by assuming a polynomial fit up to the third order. Channel-Energy calibration should follow a linear rule, check and comment on the observed behaviour. *Once you made a calibration, the amplification*

gain must not be changed. Furthermore, power supply values for the photomultiplier or the HPGe detector also can not be changed, or the calibration will not be valid anymore.
After energy calibration, the gamma spectra of all other radioactive sources should be acquired on both detectors.

4.4 Energy resolution

The energy resolution is a property that describes how accurately is possible to measure the energy of a radiation event inducing a signal in our detector system. In a practical sense, a series of monoenergetic radiation events (for example photoelectric absorption) will be processed and detected as a non-monoenergetic distribution of events due to the statistical effects of radiation-detector interactions, signal processing and background contributions. Due to these effects, it is important to always record radiation spectra with sufficient statistics. The energy distribution of such events will follow a peak-like behaviour, which can be approximated with a Gaussian function, from which a FWHM (Full-Width-at-Half-Maximum) is used to calculate the resolution:

$$R = \frac{\Delta E}{E} \tag{5}$$

where R stands for relative resolution, and ΔE = FWHM. The relative energy resolution R is thus a dimensionless fraction conventionally expressed as a percentage. The smaller the value for the energy resolution, the better the detector will be able to distinguish between radiation processes whose energies lie near each other. The energy resolution depends on the detector and also on the energy of the incident photon. *Plot R values of all measured photoelectric peaks (all isotopes), for each detector, fit the Resolution vs. Energy dependency with an appropriate function, and discuss the differences among the two detectors.* Students should also plot two spectra of the same sample but measured in each detector *superimposed in one graph* (like in Figure 7-(b)).

4.5 Source activity estimate

A radioactive source emits a certain number of photons (gamma radiation) and the detector (e.g. NaI scintillation or HPGe detector) is used to detect these photons. The number of photons emitted by the radioactive source is always larger than the number of photons observed by the detector. The activity of the source, visible by the detector at solid angle Ω, can be calculated by counting events from a single photopeak in a gamma spectrum, using the following equation:

$$A = \frac{N}{t \cdot \frac{\Omega}{4\pi} \cdot \epsilon(E_\gamma) \cdot \Gamma(E_\gamma) \cdot \omega(E_\gamma)}, \tag{6}$$

where A stands for Activity of the sample at measurement time, N is the number of counts within the Gaussian fit corresponding to a photopeak, t is the counting time in seconds (available in MCA-3 info window). The probability of gamma emission, $\omega(E_\gamma)$, can be found in Appendix B (where it is referred to as "intensity"). $\epsilon(E_\gamma)$ is the intrinsic detector efficiency. The formula is valid only for using counts registered at a photopeak energy, and this is accounted for with the $\Gamma(E_\gamma)$ factor which is called the probability of absorption (i.e. the ratio of photons captured in the photopeak compared to the total incident photons). For the NaI detector, all the factors in the activity formula can be evaluated or read-out using the information in Appendix B, C and D. *Therefore, the student should use the formula to directly calculate the activities of all the measured sources.*

For the semiconductor detector, the activity formula can not be used directly, as some parameter values are not known. The student should use the ^{152}Eu source with a calibrated activity (giving a known value on the left-hand side), and evaluate the right-hand side, for as many Eu photopeak energies as possible. All unknown parameters on the right-hand side should be grouped together as $F(E_\gamma)$, so that they can be fitted as a function of energy. The data points should follow a straight line in a log-log $F(E_\gamma)$ plot. *After this, equation 6 can be used to calculate the activities of other uncalibrated sources.*
Compare the activities obtained by two detectors and comment on the possible sources of error.

4.6 Analysis of an energy spectrum

The interpretation of gamma spectra is sometimes difficult due to the interaction of gamma radiation with the shielding material, wherein additional features, not directly related to gamma photons, appear in the spectrum [1]. The correct interpretation of the features of a gamma radiation spectrum is an important skill that students will acquire during this experiment. To prove it, students should take one spectrum (preferably from ^{137}Cs measurement), *indicate various spectral features*, as represented in Figure 3, and also *calculate the position of the Compton edge* (and compare it to the theoretically expected value).

5 Conclusion

In the gamma spectroscopy experiment, students have learned how to use two different types of gamma detectors: the thallium-activated sodium iodide detector, NaI(Tl); and the high-purity germanium detector, HPGe. Both the scintillator and the semiconductor detectors present advantages and disadvantages. In this section, students should summarize their findings and discuss the pros and cons of each detector.

References

[1] K. Buchtela. Radiochemical methods|gamma-ray spectrometry. In Paul Worsfold, Colin Poole, Alan Townshend, and Manuel Mir, editors, *Encyclopedia of Analytical Science (Third Edition)*, pages 15 – 22. Academic Press, Oxford, third edition edition, 2019.

[2] R. B. Firestone, L. P. Ekstrom, and S. Y. F. Chu. WWW Table of Radioactive Isotopes. In *APS Division of Nuclear Physics Meeting Abstracts*, APS Meeting Abstracts, page CE.13, October 1999.

[3] G.R. Gilmore. *Practical Gamma-Ray Spectrometry*. John Wiley and Sons,Inc., 2008.

[4] G.F. Knoll. *Radiation Detection and Measurements*. John Wiley and Sons,Inc., 2010.

[5] W.R. Leo. *Techniques for Nuclear and Particle Physics Experiments*. Springer Berlin Heidelberg, 1987.

[6] ORTEC. Gamma-ray spectroscopy. https://physlab.org/wp-content/uploads/2016/04/Ortec-AN34-Experiment-03.pdf.

[7] M.J. Simon. Directives for the use of radioactive sources at physikpraktikum. 2017.

APPENDIX

A Radioactivity units and radiation protection

The activity of radioactive sources can be expressed in several different units. In this experiment, the student will use the most common unit - Becquerels (Bq), with 1 Bq = 1 radioactive decay per second. This unit does not distinguish between emitted radiation types, alpha, beta, gamma, neutron.
Emitted radiation particles are absorbed by air or any other material which they interact with. Students will work with radioactive sources that emit gamma radiation at all angles with equal probability, and the absorbed dose by the detector will depend on the solid angle between the source and the opening window to the detector.

Radiation protection involves considerations about the radiation dose absorbed by the human tissue. Generally, different types of radiation have different levels of damaging effects. Furthermore, some tissue types are more sensitive to radiation effects than others. However, the sources used in the experiment are low activity and low ionizing radiation sources which are safe to work with in the experimental student lab. For more information about source handling please refer to the safety directives available on the course web pages [7]. Students are also encouraged to read a more detailed overview of the radiation protection practices and radioactivity measurement in the nuclear laboratory [5, Chapter 3].

B Table of radioisotope information

22Na

Z	11
Half life	2.6 y
Atomic mass	21.9944367 amu

Energy (keV)	Intensity	Remarks
0.84	0.12530%	XK
511	179.79000%	AN
1274.53	99.94400%	

40K

Z	19
Half life	1.28E+09 y
Atomic mass	39.9639987 amu

Energy (keV)	Intensity	Remarks
1460.75	10.70000%	A

60Co

Z	27
Half life	5.27 y
Atomic mass	59.9338219 amu

Energy (keV)	Intensity	Remarks
346.95	0.00780%	A
467.20	0.00040%	A<
826.18	0.00550%	A
1173.23	99.86000%	A
1332.51	99.98000%	A
2158.70	0.00080%	A
2505.75	0.00001%	A

134Cs

Z	55
Half life	2.06 y
Atomic mass	133.906713 amu

Energy (keV)	Intensity	Remarks
31.82	0.17000%	AX
32.19	0.33000%	AX
36.4	0.09000%	AX
37.3	0.02000%	AX
242.89	0.02100%	A
326.45	0.01440%	A
475.35	1.46000%	A
563.26	8.38000%	A
569.29	15.43000%	A
604.66	97.60000%	A
795.76	85.40000%	A
801.84	8.73000%	A
1038.5	1.00000%	A
1167.86	1.80000%	A
1365.13	3.04000%	A

207Bi

Z	83
Half life	38 y
Atomic mass	206.978455 amu

Energy (keV)	Intensity	Remarks
10.60	35.00000%	AX
72.80	23.00000%	AX
74.97	38.60000%	AX
84.80	14.00000%	AX
87.30	4.00000%	AX
511.00	0.02000%	A
569.67	98.00000%	A
897.30	0.16000%	A
1063.62	77.00000%	A
1442.00	0.15000%	A
1770.22	7.00000%	A

137Cs

Z	55
Half life	30.1 y
Atomic mass	136.907085 amu

Energy (keV)	Intensity	Remarks
31.82	1.92000%	AX
32.19	3.70000%	AX
36.4	1.04000%	AX
37.3	0.22000%	AX
661.62	84.62000%	A

152Eu

Z	63
Half life	12.7 y
Atomic mass	151.921741 amu

Energy (keV)	Intensity	Remarks
39.52	16.00000%	AX
40.12	30.00000%	AX
42.31	0.30000%	AX
43.00	0.50000%	AX
45.40	9.00000%	AX
46.60	2.10000%	AX
48.70	0.15000%	AX
50.00	0.04000%	AX
121.78	29.24000%	A
148.00	0.00546%	A<
207.40	0.00737%	A
209.20	0.00819%	A
212.48	0.02075%	A
238.80	0.06824%	A
244.67	7.61600%	A
251.62	0.07643%	A
269.40	0.00328%	A
271.03	0.07643%	A
275.40	0.03276%	A
285.80	0.00682%	A<
295.95	0.43950%	A
315.18	0.04368%	A
316.00	0.00491%	A
324.90	0.07780%	A
329.41	0.12690%	A
330.90	0.00628%	A
340.50	0.02320%	A
344.30	27.00000%	A
352.00	0.01829%	A
367.73	0.87350%	A
385.70	0.02320%	A
411.09	2.26400%	A
416.07	0.10650%	A
423.70	0.00546%	A<
444.00	2.83900%	A
444.00	0.31390%	A
482.70	0.02730%	A
488.46	0.40950%	A
493.60	0.04095%	A
493.70	0.02621%	A
493.90	0.01556%	A
496.30	0.00546%	A
496.40	0.00273%	A
503.37	0.15010%	A
520.22	0.05459%	A
523.20	0.01092%	A
527.30	0.00955%	A
534.30	0.03822%	A
535.30	0.00546%	A
556.50	0.02047%	A
561.40	0.00273%	A
563.97	0.51590%	A
566.50	0.12280%	A
586.22	0.47220%	A
616.90	0.01092%	A
644.30	0.00819%	A
656.51	0.15010%	A
664.30	0.00546%	A
671.30	0.02184%	A
674.60	0.13650%	A
675.00	0.02730%	A
678.61	0.47770%	A
686.80	0.03276%	A
688.60	0.84620%	A
703.60	0.01556%	A
712.00	0.01365%	A<
712.70	0.09008%	A
719.40	0.27300%	A
719.40	0.06005%	A
727.90	0.00928%	A
764.92	0.19110%	A
769.15	0.07643%	A
778.90	12.99000%	A
794.70	0.03003%	A
805.20	0.01365%	A
810.51	0.32760%	A
839.70	0.01692%	A
841.40	0.16380%	A
867.39	4.17600%	A
901.04	0.07643%	A
919.40	0.40950%	A
919.60	0.00546%	A
926.22	0.27300%	A
930.76	0.07370%	A
936.80	0.00218%	A
959.50	0.01365%	A
963.40	0.12010%	A
964.00	14.58000%	A
974.40	0.01092%	A
990.05	0.03276%	A
1005.06	0.65510%	A
1085.80	10.29000%	A
1089.82	1.72000%	A
1109.20	0.17740%	A
1112.07	13.58000%	A
1171.00	0.03549%	A
1206.10	0.00819%	A
1212.89	1.44700%	A
1249.80	0.17740%	A
1261.24	0.03549%	A
1292.74	0.10100%	A
1299.19	1.70600%	A
1313.50	0.00382%	A
1334.30	0.00137%	A
1347.90	0.01774%	A
1363.84	0.02730%	A
1390.40	0.00410%	A
1408.08	21.21000%	A
1457.95	0.51860%	A
1528.65	0.30030%	A
1538.20	0.00218%	A
1558.20	0.00082%	A
1605.62	0.00792%	A
1608.33	0.00546%	A
1647.33	0.00655%	A
1769.13	0.00901%	A

C Data for NaI detector

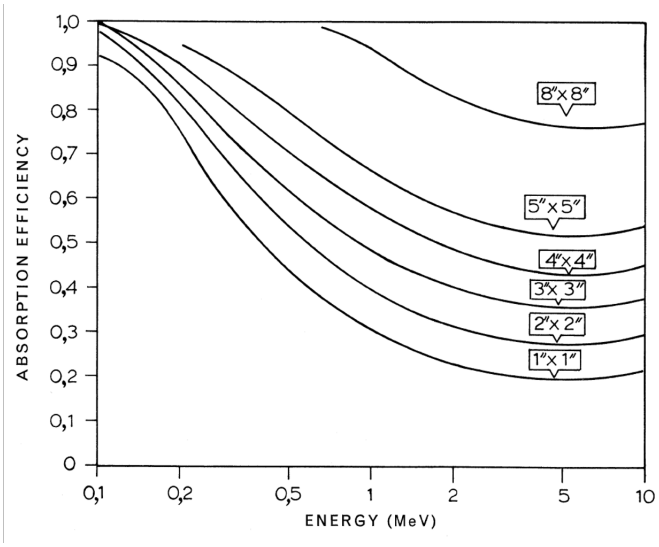

Figure 8: Absorption efficiency of gamma radiation with NaI detectors.

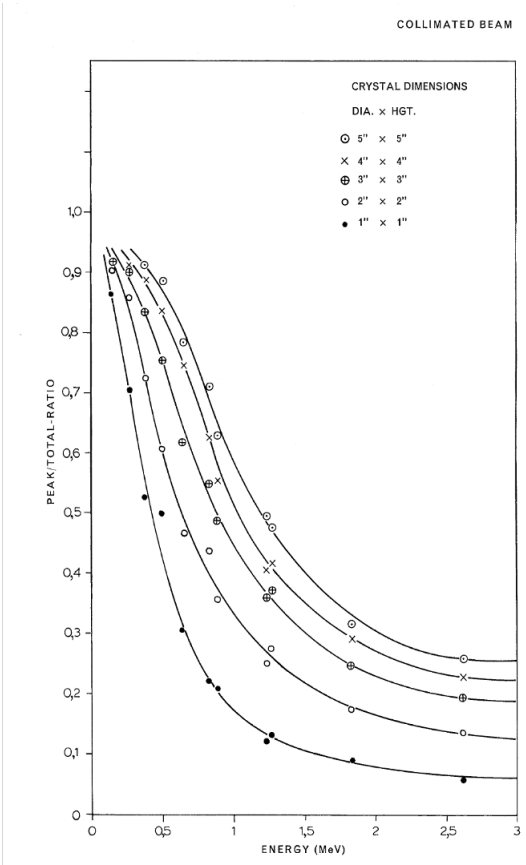

Figure 9: Ratio of photoabsorption events to total collected events for gamma spectroscopy with NaI detectors.

D Calculation of the solid angle for NaI scintillator

The geometry of the detector setup needed for the calculation of the solid angle is shown in Figure 10. The crystal diameter is $2 \cdot r_d = 1.25'' = 31.75$ mm with a thickness of $a_d = 1'' = 25.4$ mm. The source is located at a distance $a_0 = 35$ mm from the detector. The lead-collimator limits part of the solid angle between the source and the detector entrance. This results in two regions of possible gamma-ray paths with different detection response probabilities. To calculate the activity formula, a product of the solid angle Ω and the intrinsic detector efficiency ϵ must be evaluated separately (by numerical integration) for these two regions and added together.

First case: For gamma rays passing through directly to the detector, within the aperture formed by the collimator ($r_0 = 10$ mm). These gamma rays travel the distance s_0 in the detector. Express s_0 as a function of the radius r. Detection efficiency is given as $\epsilon = \left(1 - e^{-\mu_1(E) \cdot s_0}\right)$. Here $\mu_1(E)$ is the linear attenuation coefficient for sodium-iodide (coefficient value depends on the gamma energy). Product $\Omega\epsilon$ is evaluated by integrating:

$$\Omega\epsilon = \frac{2\pi}{a_0^2} \int_0^{r_0} r \cdot \epsilon \cdot \mathrm{d}r \tag{7}$$

Second case: For gamma rays that are emitted from the source at larger angles, one needs to account for initial absorption in the lead (along s_2 portion of the path) and detection efficiency due to interaction with the detector (along s_1 portion of the path). Express s_1 and S_2 as functions of r. Evaluate the $\Omega\epsilon$ product for this case by integrating:

$$\Omega\epsilon = \frac{2\pi}{a_0^2} \int_{r_0}^{r_d} r \cdot \left(1 - e^{-\mu_1(E) \cdot s_1}\right) \cdot \left(e^{-\mu_2(E) \cdot s_2}\right) \cdot \mathrm{d}r \tag{8}$$

Here μ_2 is the linear absorption coefficient of lead.

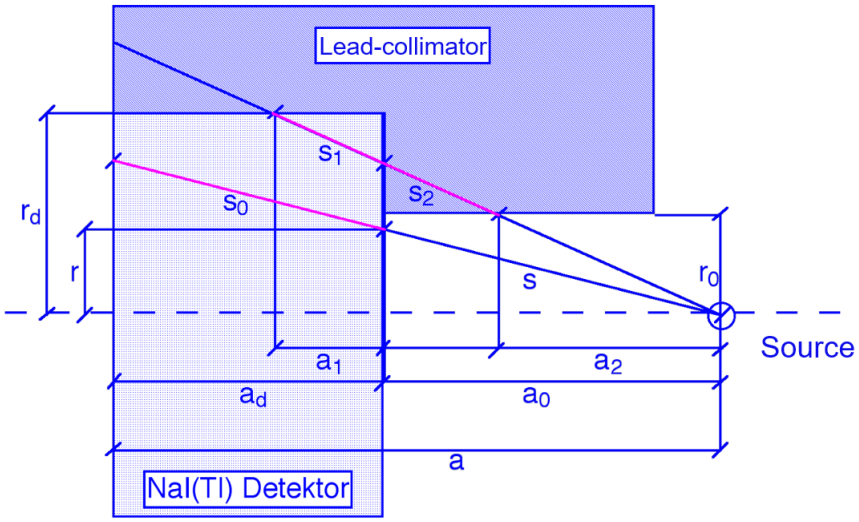

Figure 10: Schematic view of two possible gamma-ray paths between the source and the NaI detector. Note the labels used to identify different elements of the geometry needed in solid angle calculation.