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$\gamma\textsc{-}\textsc{Absorption}$ Experiment

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Abstract

Photons interact with matter by processes such as the photo-electric effect, Compton scattering, and pair formation. Due to this interaction the intensity of radiation passing matter decreases exponentially with penetration depth. This exponential decay is characterized by the so called absorption coefficient. This coefficient depends on material properties and the photon energy. The goal of this experiment is to understand the interaction of photons with matter, to verify the exponential absorption law and to determine the absorption coefficients for a given material at various photon energies. In addition, these measurements imply the familiarization with basics of detectors and electronics.

Chapter 1 Introduction

Photons interact with matter by electromagnetic processes such as the photo-electric effect, Compton scattering and pair formation. Due to this interaction the intensity of radiation passing matter decreases exponentially with penetration depth. The exponential decay of the intensity as a function of the path length in the material is described by the so called absorption coefficient. The basic theory regarding photon-matter interaction and the absorption coefficient will be presented in this chapter.

1.1 Electromagnetic radiation

Electromagnetic radiation is a self-propagating wave in vacuum or in matter. It is classified into several types as shown in Fig 1.1 according to the frequency of its wave; these types include (in order of increasing frequency and decreasing wavelength): radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma-rays (γ -rays).

Electromagnetic radiation exhibits both wave properties and particle properties at the same time. In the classical picture, it may be seen as a transverse wave (oscillation transverse to the direction of propagation) oscillating with a certain frequency which is measured in Hertz $(1 \text{ Hz}=1 \text{ s}^{-1})$.

In the particle model, electromagnetic radiation is made of discrete packets of energy, called photons. The photon frequency (which corresponds to the frequency of the electromagnetic wave) is proportional to the particle energy. The main physical properties of the photon are

Energy	$E = h\nu$		
Wavelength	$\lambda = \frac{c}{\nu}$		
Velocity	v = c	(1	11)
Mass	m = 0	()	1.1)
Momentum	$p = \frac{h\nu}{c} = \frac{h}{\lambda}$		
Angular moment	$L = \pm \frac{h}{2\pi} = \pm 1\hbar$		

where c = 299792458 m/s is the speed of light and $h = 6.6 \times 10^{-34}$ Js is Planck's constant.



Figure 1.1: The electromagnetic spectrum [1].

In this experiment we are dealing with the so called γ -rays, which are produced by sub-atomic particle interactions such as electron-positron annihilation, neutral pion decay, radioactive decay, fusion, fission or inverse Compton scattering in astrophysical processes or accelerator facilities. Gamma-rays typically have frequencies larger than 1019 Hz corresponding to energies larger than 100 keV and wavelengths less than 10 pm. Gammaphoton from radioactive decay typically have energies of a few hundred keV and almost always less than 10 MeV.

The distinction between γ - and X-rays has changed in recent decades. In older literature the distinction between γ - and X-ray was based on their wavelength. Radiation with wavelength shorter than the arbitrary wavelength of 10^{-11} m was defined as γ -rays. Radiation with wavelength between 10^{-8} m to 10^{-11} m (energy from 120 eV to 120 keV) was defined as X-ray [13]. Nowadays the two radiation types are distinguished by their origin: X-rays are emitted by electrons outside the nucleus, while γ -rays are emitted by the nucleus.

1.2 Interaction of photons with matter

Photons interact with matter mainly by the following processes [11, 14]:

• Elastic scattering (Rayleigh- and Thomson- scattering)



Figure 1.2: (a) Compton scattering at quasi-free electrons of the atoms. (b) Photo-effect which is the absorption of γ -radiation from electrons bound in atoms (c) Absorption of γ -radiation by the nucleus. (d) Pair (e^+e^-) production. [11]

- Inelastic scattering (Compton effect)(Fig. 1.2a)
- Absorption in the electrons shells of the atoms (Photo-effect)(Fig. 1.2b)
- Absorption in the nucleus of the atoms (nuclear photo-effect)(Fig. 1.2c)
- Production of other particles (e.g. pair production)(Fig. 1.2d).

These processes which finally transfer energy to the electrons (electron current) are used for the detection of γ -radiation.

1.2.1 Rayleigh scattering

Rayleigh scattering is important for photon energies smaller than the electron binding energy (E_b) i.e., $h\nu < E_b$. Electrons of the material are brought into oscillation by the radiation field (at the same frequency of the radiation field). These oscillating electrons will re-emit radiation at their oscillation frequency. This emission can be understood also in the classical picture of electrodynamics where charged particles – when accelerated – emit radiation. The Rayleigh cross section is proportional to ν^4 (reason for the blue sky).

1.2.2 Compton scattering

At higher energies $h\nu > E_b$ the inelastic process i.e., Compton scattering becomes important. It describes the scattering of photons on quasi-free electrons. In such a scattering, the photon transfers a portion of its energy to the electron and it is deflected from its



Figure 1.3: The Compton effect. [2]

original direction by an angle θ as shown in Fig. 1.3. The electron (assumed to be initially at rest) gains a kinetic energy of

$$E_e = E_\gamma - E'_\gamma \tag{1.2}$$

where E_{γ} and E'_{γ} are the energy of the photon before and after scattering respectively. From energy and momentum conservation it can be derived that the energy of the scattered photon is

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e c^2} (1 - \cos \theta)} \tag{1.3}$$

where $m_e c^2$ is the electron rest mass energy (511 keV). Because all scattering angles are possible, the energy transferred to the electron can vary from zero ($\theta = 0$, i.e. no scattering) to a maximum for back-scattered ($\theta = \pi$) photons. This maximum recoil energy of the electron is known as *Compton edge* and can correspond to a large fraction of the incoming photon energy. Some of the original energy however is always retained by the photon, even in this latter extreme case (i.e., Compton edge $\langle E_{\gamma} \rangle$). In fact the maximal energy transferred to the electron is given by

$$T_{max} = \frac{h\nu}{1 + \frac{m_e c^2}{2h\nu}}.$$
(1.4)

Compton scattering is a medium energy phenomena.

1.2.3 Photoelectric effect

In the photoelectric absorption, the photon interacts with an atomic electron. The result is that the photon is absorbed and the electron (also called *photo-electron*) is ejected from the atom with a kinetic energy of

$$E_e = E_\gamma - E_b \tag{1.5}$$

where E_b is the binding energy of the electron in its original shell. Note that a free electron can't absorb a photon and fulfill both momentum and energy conservation. This

means that photoelectric absorption can occur only on bound electrons, with the nucleus absorbing the necessary recoil momentum to guarantee momentum conservation.

As a results of the electron emission from the atom, an ionized atom with a vacancy in one of its shells is produced. This vacancy is quickly filled from a free electron of the medium or from rearrangement of electrons from other shells via radiative or Auger transitions [8] as shown in Fig. 1.4. The emission of light when an orbital electron of an atom or a molecule relaxes spontaneously to a lower state (to fill the vacancy) till the ground state is reached is called fluorescence. The X-ray energy emitted in this process equals the difference between the two binding energies of the corresponding shells. The peaks in the characteristic X-ray spectrum are named as K, L, M or N peaks depending on where they originated. Therefore, one or more characteristic X-ray photons are typically emitted together with the photo-electron. In most of the cases they are immediately reabsorbed (photoelectric absorption on less bound states), but they could also escape from the material.



Figure 1.4: The process of X-ray fluorescence in detail [8]. (a) Electron from K shell is ejected by external X-, γ -ray excitation creating a vacancy. (b) An electron from L or K shell "jumps" to fill the vacancy emitting a characteristic X-, γ -ray. This in turn produces a vacancy in L or M shell. (c) If the vacancy is created in the L shell, an electron from M or N shell "jumps" to occupy the vacancy emitting a characteristic X-, γ -ray unique to this element. (d) If the excitation energy from the inner atom is transferred to one of the outer electrons causing it to be ejected from the atom this is called the Auger effect.

1.2.4 Pair production

The pair production mechanism is the conversion of a photon into an electron-positron pair. For this process to occur, the photon must have at least an energy of 1.022 MeV (i.e. $2 \times m_e c^2$). Since the conservation laws of impulse and energy have to be respected, pair production cannot occur without the presence of the nucleus (or another photon). This is the reverse effect to electron-positron annihilation. However, the probability of this interaction remains practically negligible until the photon energy approaches several MeV. The pair production effect is thus completely irrelevant for our experiment.

1.2.5 Nuclear resonance absorption

A nucleus can be excited to a higher state by absorption of a γ -quantum. Since nuclear resonances are sharp $(\Delta \nu / \nu \approx 10^{-10})$ and the transition matrix elements are proportional to r_N^2 where r_N is the nuclear radius, the probability of resonant absorption is very small (see Mössbauer-effect).

1.2.6 Total cross section

The relative importance of the three processes described above depends not only on the energy of the photon, but also on the absorbing material. As a very rough rule, the cross section for photoelectric absorption and pair production are strongly dependent on the atomic number Z (going roughly as Z^5 and Z^2 , respectively), while the Compton process only varies linearly with Z. In the energy region of interest for the present experiment (~ 100 keV), both the photoelectric and the Compton effects will play an important role.

A photon detector first must act as a conversion medium, in which incident γ -rays have reasonably high probability to interact and produce free electrons and vacancies, and then it has to serve as a detector for these electrons. In gamma-ray spectroscopy, i.e. photon energy measurement, the directly measured quantity is the number of created free electrons to which the photon has transferred its initial energy (all or part of it). In an unrealistic case in which only photoelectric absorption can occur (e.g. very high Z material and low energy γ) the typical detected energy spectrum would look like the one in Fig. 1.5(a): one single peak at a total electron energy corresponding to the energy of the incident photon. If Compton interaction occurs, the recoil electron will have a continuous energy distribution, from zero ($\theta = 0$) to the Compton edge ($\theta = \pi$), and the detected energy spectra would be as shown in Fig. 1.5(b) if the scattered photon escapes the detector volume. In a realistic case, when both the photoelectric and the Compton effects may occur in the same detector, the measured energy spectrum would be a superpositions of the two effects as shown in Fig. 1.5(c). In the sketch an idealized infinite energy resolution is assumed (i.e. sharp edges); in reality, the detector energy resolution smooths the shape of the spectrum. The photo-peak is typically a Gaussian. From its width, the energy resolution R_{FWHM} (Full Width Half Maximum) is usually



Figure 1.5: Sketches of the detected energy spectra. (a): for photoelectric absorption, (b) for only Compton scattering without detection of the scattered photon, (c): both interactions.

derived:

$$R_{FWHM} = \frac{\Delta E}{E} = 2\sqrt{2} \times \frac{\sigma}{E} \simeq 2.36 \times \frac{\sigma}{E}.$$
 (1.6)

1.2.7 Photon absorption law

Experiments show a fractional decrease of the photon intensity I when crossing a thin homogeneous material of thickness dx ($dx \ll \mu$) i.e. $dI \sim -I$ (the minus indicate a decrease) and $dI \sim dx$ and thus

$$-\frac{dI}{I} = \mu \, dx \tag{1.7}$$

with the proportionality constant μ called the *linear absorption coefficient*. The linear absorption coefficient depends on the substance considered, its density, and the photon energy. The absorption coefficient relates to the atom-photon interaction cross section as

$$\mu = \sigma \cdot n \tag{1.8}$$

where n is the density of atoms in the material ($atoms/cm^3$).

Integrating Eq. (1.7) gives

$$I(x) = I_0 e^{-\mu x}$$
(1.9)

with I_0 the intensity of the incident beam and I(x) the intensity of the transmitted beam after passing through a thickness x [13]. The coefficient μ is proportional to the mass density ρ . Thus the quantity (μ/ρ) is a constant of the material and independent of its physical state. This latter quantity, called the mass absorption coefficient, is tabulated in [9]. Equation (1.9) can be written in a more common form as

$$I(x) = I_0 e^{-(\mu/\rho)\rho x} . (1.10)$$

If a substance contains more than one element, its mass coefficient is simply the weighted average of the mass absorption coefficients of its constituent elements. If w_1, w_2 , etc. are

the relative material fractions, the mass absorption coefficient of the substance is given by

$$\frac{\mu}{\rho} = w_1 \frac{\mu_1}{\rho_1} + w_1 \frac{\mu_2}{\rho_2} + \cdots$$
(1.11)

and expressed in $[cm^2/g]$.



Figure 1.6: Mass attenuation coefficient of iron with the contributing processes shown separately [3]. In figure legend "coherent scattering" stand for elastic processes (Rayleighand Thomson- scattering) and "Incoherent scattering" for Compton scattering.

Chapter 2

Experimental setup

The setup which is schematically given in Fig. 2.1 and Fig. 2.2 is composed by the following parts:

- Radioactive γ -sources (¹³³Ba and ²⁴¹Am) mounted on a revolving wheel inside a protection (absorbing) metallic box.
- Samples of various materials and thickness used as absorbers mounted on on a second revolvable wheel.
- An energy resolving γ -detector (Amptek XR-100T-CdTe detector) with appertaining electronic (bias and power supply, shaping amplifier, etc.)
- A PC with a digital I/O card and multi-channel analyzer used to acquire the data from the detector.



Figure 2.1: Schematic view and picture of the whole setup.

A self made bias supply (max. bias voltage 200 V) provides the power for the CdTe detector. Integrated in the detector box there is a cooled preamplifier. The detector-preamplifier output signals are successively amplified and shaped with 1 μ s shaping time with a programmable amplifier based on modules from CREMAT. For changing radioactive source or absorbing sample micro drives which are controlled from the PC are used.



Figure 2.2: The γ absorption experiment.

2.1 Sources

¹³³**Ba:** This radionuclide has a half-life of 10.51 years and is produced by fast or thermal neutron activation. ¹³³Ba converts to ¹³³Cs by electron capture in the nucleus $(e^- + p \rightarrow n + \nu)$. The decay scheme of ¹³³Ba to ¹³³Cs is illustrated in Fig. 2.3. The source has an activity of 370 kBq.

²⁴¹**Am:** It is decaying into ²³⁷Np (daughter nucleus) emitting an α -particle as shown in Fig. 2.4. As can be seen from the decay scheme various decay channel exist, the majority of which end up in an excited state of ²³⁷Np. This excited state de-excite emitting one



Figure 2.3: The decay scheme of ${}^{133}Ba$. The numbers in parentheses indicate absolute intensities [10].

or more γ -quanta (²³⁷Np^{*} \rightarrow ²³⁷Np+ γ). The Am-source used for this experiment has an activity of 37 kBq. In order to stop the produced α radiation the source is covered with a plastic foil. Therefore only γ -rays are detectable with our setup. Americium has a half-life of 433 years.



Figure 2.4: The decay scheme of ²⁴¹Am [4].

2.2 γ -detector

2.2.1 Working principle

In this experiment we make use of a semiconductor detector. It is a pn-junction (Cd-Te) which is formed by joining p-type and n-type semiconductors. Due to difference in the concentration of electrons and holes between the two materials, there is an initial diffusion of holes towards the n-region and a similar diffusion of electrons towards the p-region. As a consequence, a region where charge built-up occurs is formed (Fig. 2.5(a)). Since the two materials are initially neutral, the p-region near the junction becomes negatively and the n-region positively charged. The region where this occurs is named *depletion zone* or *space charge region*. This charge built-up generates an electric field and thus an electric potential as illustrated in Fig. 2.5(c) and (d) respectively.



Figure 2.5: pn-junction working principle [5].

Electron-hole pair are produced when an incoming photon (X-, γ -ray) deposit energy in the semiconductor. If this electron-hole pairs are produced in the depletion region the electric field forces electrons toward the positive space charge (n-region) and holes in the opposite direction. If electrical contacts are placed on either end of the pn-junction, a voltage signal proportional to the number of electron-hole pairs (proportional to the deposited energy) will output the preamplifier. The preamplifier converts the collected charge into a voltage signal and is connected to the detector as shown in Fig. 2.6. By applying a reverse-bias voltage to the pn-junction, i.e., a negative voltage to the p-side as in Fig. 2.1, the depletion zone will be enlarged. Thus with increasing reverse voltage (U) the sensitive volume for radiation detection increases whereas the detector capacity decreases.



Figure 2.6: Scheme of detector and preamplifier system [7].

Semiconductors have some advantages compared with gas detectors:

- Higher densities which means stronger stopping power (efficiency) and thus small size. This smallness leads to short drift times and thus better time resolution.
- The energy necessary to produce an electron-hole pair is generally smaller than the energy needed to ionize an atom. Given a certain amount of deposited energy more charge carrier pairs are thus produced in a semiconductor. This leads to a better energy resolution.



Figure 2.7: Preamplifier output pulse. Its pulse height is proportional to the number of electron-hole pairs produced in the active region of the detector.

2.2.2 The AMPTEK XR-100T-CdTe γ -detector

Model XR-100T-CdTe is a high performance X-ray and γ -ray detector, preamplifier, and cooler system using a $3 \times 3 \times 1 \text{ mm}^3$ (or $5 \times 5 \times 1 \text{ mm}^3$) Cadmium Telluride (CdTe) diode

detector mounted on a two-stage thermoelectric cooler. On the cooler side also the input FET and feedback components to the charge sensitive preamplifier are mounted [6].

This charge sensitive preamplifier integrates the charge produced by ionizing radiation and provides a voltage pulse, which is proportional to the amount of electron/hole pairs produced. The shape of the preamplifier output signal has a "linear" rise-time in the ns time scale (when charge integration occurs) and has a decay time in the ms range (when the capacitor for charge integration is discharged). The height of the signal pulse is in the mV range.

All the critical connections between the detector and the preamplifier have been made internally to the XR-100T-CdTe to ensure quick, first time operation by the user. The XR-100T-CdTe is provided complete with BNC connectors and power cable. Signal polarity is negative.



Figure 2.8: Model of the detector systems. Depending of which type the material of the detector changes [7].

Ionizing radiation create electron/hole pairs in the depletion zone of the CdTe crystal. For producing one electron/hole pair 4.43 eV of energy is needed. In order to facilitate the electron/hole collection a bias voltage of **200 V** is applied. Therefore the sensor and input FET transistor have to be cooled, otherwise it will cause excessive leakage and eventually breakdown [6]. The XR-100T-CdTe is capable of detecting energies from a few keV to several hundreds of keV.

2.2.3 CdTe vs. Si-Pin

Depending on the application, either a Si-Pin or a CdTe sensor is used. For energies below 25 keV the Si-Pin is the detector of choice, due to its better energy resolution, lower background counts and its good overall efficiency. Above 25 keV, CdTe is the detector of choice. Greater stopping power favors its utilization [6] [7]. Si-Pin detectors almost always have better spectral characteristics, while CdTe detectors have better efficiency and shorter shaping times, which is helpful at high count rates. A model of such detectors can be seen in Fig. 2.11.

2.3 Electronic

2.3.1 Bias supply

Bias voltage and detector power are provided by a supply built in a NIM module. Once the NIM bin is turned on the AMPTEK XR-100T-CdTe γ -detector is powered and the bias voltage (up to 200 V) can be adjusted by the knob on the front side of the module. The actual bias voltage is displayed also on the module front panel.

2.3.2 Shaping amplifier

The shaping amplifier serves two main purposes:

- amplify the input signal
- shape the input signal to a convenient form for further processing.

Gaussian shaping amplifiers (as the one used in this experiment) accept a step-like input pulse as illustrated in Fig. 2.11 and produce an output pulse shaped like a Gaussian. This reshaping serves to filter much of the noise from the input signal and provide a quickly restored baseline to allow for higher counting rates. The so called shaping time is defined as the time-equivalent of the standard deviation of the Gaussian output pulse.



Figure 2.9: Shaping amplifier operation principle. An input pulse as shown in top figure will lead to an output pulse as shown in the bottom figure.

The shaping amplifier used in this experiment consists of a NIM module, where all I/O connectors are on the front side. The amplification is adjustable in 16 steps either by remote control (from the PC) or by the knob on the front side of the module. For the pulse height analysis an output signal with a shaping time of 1 μ s is provided on the connector labeled with "Out". Additionally a fast output signal with a shaping time of

100 ns and a single channel analyzer is included. Both options are not needed for this experiment.



Figure 2.10: Picture of the programmable shaping amplifier.

2.4 ADC card

The height of the Gaussian shaped analog signal is converted into the digital number by the MCA-3 multichannel analyzer from FAST COM TEC. The MCA-3 series is a family of PC-based, software controlled PCI-bus Multichannel Analyzers. The design is capable of converting incoming signals at up to 1,000,000 events/s. Two multi scaling inputs accept counting rates of more than 400 MHz. The minimum dwell-time is 100 ns. The large data memory can be segmented to enable to accumulate successive measurements. The board provides ultra fast pulse height analyzing 8k ADC with 500 ns conversion time for Pulse-Height Analysis.



Figure 2.11: Multichannel analyzer card of FAST ComTec [12].

2.5 Measurement control

The hole experiment is controlled via two computer programs: the MCDWIN program for data acquisition and the SampleChanger for changing either the sample or the source.

The MCA software provides the possibility to acquire a pulse height spectrum and save the collected data into a data file including the pulse height spectrum and measurement time for offline analysis. A region of interest can be defined by the right mouse bottom. For a first on-line analysis a Gaussian fit can be applied on a region, which also can be selected by the right mouse bottom.

Chapter 3

Measurements and tasks

The following steps are suggested for the experiment:

- Check radiation protection.
- Optimize setup settings: amplifier gain, ADC resolution and range.
- Acquire energy spectra of the two radioactive sources (without material absorption). Understand the measured spectra, i.e., identify the peaks.
- Acquire an energy spectrum for the various sample thicknesses and sources. From these measurements the absorption coefficients will be determined.

3.1 Check radiation protection

In Appendix you find some definitions concerning radiation doses. Use a dosimeter (see the technical advisers) and measure the dose you are getting during your experimental work. Check if the dose is a problem concerning radiation protection.

Question: Which is the present activity of the 133 Ba source when in June 2007 it had an activity of 370 kBq?

3.2 Turn on setup

- Make sure that the potentiometer of diode power supply is "Zero".
- Switch on the crate power supply.
- Make sure that pulse generator is off.
- Remove the red protection cover in front of the detector.



Figure 3.1: Mass attenuation coefficient for lead (Pb) as a function of the incoming photon energy. [9]

- Choose an appropriate position for the detector and don't change the position for all the consecutive measurements.
- Turn on slowly (in ca. one minute) the detector voltage to 200 V. You can read the actual voltage in Volt directly from the readout.
- Turn on computer
 - Open MCA-3 program \rightarrow a windows as in Fig. 3.2 will pop-up.
 - Open MotorControl.exe \rightarrow a windows as in Fig. 3.3 will pop-up.
 - Select "Remote" to operate the experiment from the PC.
 - Select "Source" if you want to switch between radioactive sources by the buttons "No Source", "241Am" and "133Ba". Then press "Set position".
 - Select "Sample" if you want to rotate the external wheel with the various absorber materials (Ti, Pb and Brass) of various thickness. Then press "Set position".



Figure 3.2: The MCA-3 graphical interface.

Motor Control				
		Remote off Γ Switch On / Off		
⊏ Sample		□ Source		
Position Selected Position	0	No_Source 241Am 1338a	Amplifier Level	
Set Position Re	set Wheel	Selected Source -	Set Level	
	Stop			
Steps to Zero Step 1 Timeout	s to Position 0	Light Barrier		
Time left -				

Figure 3.3: The MotorControl.exe graphical interface.

3.3 Find settings

Before acquiring the spectra for the determination of the absorption coefficients it is necessary to optimize gain, resolution and range of the data acquisition system.

• Rotate the "Sample" wheel via the MotorControl.exe graphical interface so that no sample is positioned between detector and source. Select "Sample", set "Position" to 1, and press "Set Position". Make sure that the hole is in front of the detector.

- Use the ¹³³Ba source to find the settings. On the the MotorControl.exe graphical interface select "Sample", set "Position" to 2, and then press "Set position". For safety reasons there is a timeout implemented, which either removes the source or covers the source by a led sample after 1800 sec!
- Start to collect an energy spectrum by pressing the "play" symbol in the MCA-3 program. Switch the display to logarithmic scale.
- Adjust the gain of the shaping amplifier, so that the allocated ADC channels are well exploited. In order to remotely change the gain, utilize the MotorControl.exe graphical interface. Set the desired "Amplifier Level" which is ranging from 1 to 12 and then press "Set Level". After having changed the amplifier settings restart a new measurement to better visualize the changes.
- Select an appropriate ADC resolution (number of x-axis bins). What is appropriate? This can be adjusted in the MCA program graphical interface by selecting "Option" → "Range preset" → "Range" → Ok.
- When you have set amplifier gain, ADC resolution and the measurement time you do not have to modify them any more during the experiment.

3.4 Line identification of the ¹³³Ba source

- Make sure that there isn't any absorbing material between the radioactive source and the detector.
- Make sure that you are measuring the ¹³³Ba source. Sample position=1.
- Start a measurement by pressing the button "play".
- A spectrum as shown in fig. 3.4 should appear. Identify the peaks marked by red arrows according to the decay scheme 2.3 and note in your logbook the ADC position and amplitudes of this peaks. The position of the peak can be read out with the PC mouse. The mouse position will be displayed below the energy spectrum in the MCA-3 graphical interface by clicking the left mouse button.
- Set a region of interest (**ROI**) for the 383 keV line.
- Continue the data acquisition until the statistical error for the 383 keV line is less than 5% (**Poisson statistics**).
- Move the source in position 3 (where the radiation is absorbed by 6 mm Pb).
- Create a new directory with your name on the Desktop.

- Save the measured energy spectrum in .txt file format in your directory. Note that two files will be created, a .txt file with the data of the spectrum (ADC channel versus number of events), and a .mcd file which contains the setting information, like measurement time and so on.
- Draw on the logbook the measured spectrum and understand it.



Figure 3.4: Energy spectrum of the ¹³³Ba source.

3.5 Line identification of the the ²⁴¹Am source

- Repeat the same measurement of Sec. 3.4 with the ²⁴¹Am source.
- Identify the 59 keV line of ²⁴¹Am and fit it with a Gaussian function. For a first on-line analysis do the following steps: select the region of interest (the photo-peak) with the right mouse button. Pressing the button with the Gaussian icon (placed on top line of MCA-graphical interface) will lead to a Gaussian fit of the peak. From the fit you will precisely determine the peak centroid position and its width (FWHM). Write down in your logbook these values. Using Eq. (1.6) determine the detector resolution.
- Again measure until the statistical error is less than 5%.



Figure 3.5: Energy spectrum of the ²⁴¹Am source.

3.6 Energy calibration

From the known energy of the various peaks (see Fig. 2.4 and Fig. 2.3) you can perform an energy calibration (ADC/keV). The aim of the calibration is to assign a physical value (in keV) to the ADC channels.

- Plot the peak positions [ADC channel] versus the peak energy in [keV] for the 59 keV line of ²⁴¹Am and the 356 keV together with 383 keV peak of ¹³³Ba.
- Fit the resulting plot with a linear function with offset. Is the detector linear? How large is the pedestal?
- What is the energy resolution in keV for the 59 keV line of 241 Am?

3.7 Determination of the Absorption-Coefficient μ

- Set the ROIs for the 59 keV line of $^{241}\mathrm{Am}$ and the 356 keV together with 383 keV peak of $^{133}\mathrm{Ba}.$
- For the various thicknesses of the materials listed in table 3.1 acquire the energy spectra (except for ²⁴¹Am on Pb). Stop the measurement, when 5% statistical error is reached. Do not forget to save the data after each measurement.

- For each measured spectrum (the one without absorbing material included) determine the amplitude of the 383 keV, 356 keV and 59 keV peaks i.e. I(d) for the various photon energies.
- For each photon energy plot the peak amplitudes versus sample thickness in linear scale, i.e., I(d) versus d. Do a fit with an exponential and determine the absorption coefficient. Use errors for I(d) and include them in the fit.
- For each photon energy plot $\log (I(d)/I_0)$ as a function of d.
- Calculate the uncertainty of the $\log(I(d)/I_0)$ values by doing an error propagation.
- Do a linear fit of the last plot (accounting for the uncertainty of the $\log (I(d)/I_0)$ values) and determine the absorption coefficient and its uncertainty.
- Compare the measured coefficients with literature values [9].

Position	Material	Thickness (mm)	Density (g/cm^3)
1	0	0	
2	Pb	1 ± 0.1	11.35
3	Pb	3 ± 0.1	11.35
4	Pb	6 ± 0.1	11.35
5	Ti	4 ± 0.1	4.51
6	Ti	6 ± 0.1	4.51
7	Ti	8 ± 0.1	4.51
8	Ti	10 ± 0.1	4.51
9	Brass (CuZn39Pb3)	4 ± 0.1	8.47
10	Brass (CuZn39Pb3)	6 ± 0.1	8.47
11	Brass (CuZn39Pb3)	8 ± 0.1	8.47
12	Brass (CuZn39Pb3)	10 ± 0.1	8.47

Table 3.1: Thickness and position of the samples.

Appendix A Definitions

Extracted from Annex 1 of the Radiological Protection Ordinance (SR 814.501).

Activity Number of disintegrations per unit time. The unit of activity is the becquerel (Bq); $1 \text{ Bq} = 1 \text{ s}^{-1}$.

Activity concentration Activity per unit volume. The activity concentration is expressed in becquerels per cubic meter (Bq/m^3) .

Activity, specific Activity per unit mass. Specific activity is expressed in becquerels per kilogram (Bq/kg).

Controlled areas

- working areas for the handling of unsealed radioactive sources, as specified in Art. 69;
- areas in which air concentrations may exceed 1/20 of the guidance values specified in Annex 3 Column 11;
- 3. areas in which surface contamination may exceed the guidance values specified in Annex 3 Column 12;
- 4. areas in which people may accumulate an effective dose of more than 1 mSv per year as a result of external exposure;
- 5. areas in which equipment is operated without a full protection system;
- 6. areas designated as such by the supervisory authority.

Becquerel (Bq) Unit of activity of a radionuclide. 1 Bq = 1 disintegration per second. The becquerel supersedes the curie (1 Ci = $3.7 \cdot 10^{10} \text{ Bq}$).

Dose Quantity used to assess the health risks of ionizing radiation. Unless indicated to the contrary, the term is used in this Ordinance to mean *`effective dose*î.

Dose, absorbed The amount of energy deposited per unit mass of material as a result of interaction with ionizing radiation. The unit of absorbed dose is given the special name gray (Gy); 1 Gy = 1 J/kg.

Dose, ambient The ambient dose is taken to be

- 1. the quantity $H^*(10)$ (ambient dose equivalent) for strongly penetrating radiation;
- 2. the quantity H'(0.07) (directional dose equivalent) for weakly penetrating radiation.

Dose, ambient equivalent, H^*(10) The ambient dose equivalent $H^*(10)$ at the point of interest in the real radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius opposing the direction of the aligned field.

Dose, committed effective (E50) The effective dose that accumulates in the body over a period of 50 years as a result of the intake of a nuclide.

Dose, directional equivalent H'(0.07) The directional dose equivalent H'(0.07) at the point of interest in the real radiation field is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth of 0.07 mm on a radius in a specified direction.

Dose, effective (E) The sum of the equivalent doses in all organs and tissues weighted with the factor w_T .

 $\mathbf{E} = \mathbf{S}_T \cdot \mathbf{w}_T \cdot \mathbf{H}_T = \mathbf{S}_T \cdot \mathbf{w}_T \cdot \mathbf{S}_R \cdot \mathbf{w}_R \cdot \mathbf{D} \mathbf{T}_{T,R}$

 $D_{T,R}$ = absorbed dose in tissue T due to radiation R

 w_R = radiation weighting factor

 $w_T = tissue weighting factor (contribution of tissue/organ T to the overall risk)$

 $H_T = equivalent dose for tissue/organ T$

The special name for the unit of effective dose is the Sievert (Sv); 1 Sv = 1 J/kg.

Dose, equivalent (H) The product of the absorbed dose DT,R due to radiation R in tissue T and the radiation weighting factor w_R (cf. Dose, effective). The special name for the unit of equivalent dose is the sievert (Sv); 1 Sv = 1 J/kg.

 $H_{T,R} = w_R \cdot D_{T,R}$; for a mixture of radiation types: $H_T = S_R \cdot w_R \cdot D_{T,R}$

Dose, personal deep, H_p(10) [short form: Hp] Equivalent dose in soft tissue at a depth of 10 mm in the thoracic region.

Radiation type and energy range	Energy	Radiation weighting factor, w_R
	$< 10 { m ~keV}$	1
Protons,	10 keV to $100 keV$	1 - 5
all energies Electrons and muons,	100 keV to 2 MeV	5 - 20
all energies Neutrons	2 MeV to $20 MeV$	20 - 10
	$> 20 { m ~MeV}$	10 - 5
Protons, other than recoil protons	$> 20 { m ~MeV}$	5
Alpha particles,		
fission fragments,		20
heavy nuclei		

Table A.1: Radiation weighting factors

Table A.2: Tissue weighting factors

Tissue or organ	Tissue weighting factors, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Dose, personal surface, H_p(0.07) [short form: Hs] Equivalent dose in soft tissue at a depth of 0.07 mm in the thoracic region.

Dosimeter Instrument used to measure ambient or personal doses.

Gray (Gy) The special name for the unit of absorbed dose. 1 Gy = 1 J/kg.

Half-life The time taken for the activity of a radionuclide to lose half its value by decay.

Ionizing radiation Radiation that has sufficient energy to eject electrons from an atomic shell (ionization).

Ionizing radiation generators Equipment and devices used to generate photon or particle radiation with an energy greater than 5 keV.

Irradiator A device used for irradiation purposes, containing a sealed radioactive source. The radiation source is enclosed within shielding, to which it remains mechanically connected irrespective of the operating state.

Non-occupationally exposed persons People who could be exposed to higher-thanbackground levels of controllable radiation as a result of circumstances not related to work or training.

Occupationally exposed persons:

- could accumulate an effective dose of more than 1 mSv per year in the course of their work or training through controllable radiation exposure; or
- regularly work or undergo training in controlled areas.

Radioactivity Spontaneous disintegration of nuclides, accompanied by the emission of ionizing radiation.

Radiation sources Equipment and articles containing radioactive substances (sealed and unsealed radioactive sources) and installations capable of emitting ionizing radiation.

Radionuclide Nuclide that disintegrates spontaneously, emitting radiation.

Radionuclide generator Radioactive source with a fixed parent radionuclide producing a daughter radionuclide which can be removed by elution or by any other method.

Sievert (Sv) The special name for the unit of equivalent dose or effective dose. 1 Sv = 1 J/kg.

Sources, radioactive Sealed and unsealed sources.

Sources, sealed radioactive Radiation sources which contain radioactive substances and whose structure is such as to prevent, under normal conditions of use, any release of the radioactive substances and thus preclude any risk of contamination. The source encapsulation must satisfy the requirements of the ISO standards for the intended use and be classified as such.

Sources, unsealed radioactive Radiation sources containing radioactive substances that are capable of spreading and causing contamination.

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