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GAMMA-RAY SPECTROMETRY USING HPGE DETECTORS

Measurement guide

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1. Introduction

Gamma-ray spectrometry is concerned with the measurement of the energy, intensity and angular distribution of gamma rays emitted as the result of a nuclear process (radioactive decay and artificial or natural nuclear reactions). This laboratory practice makes it possible to deepen the understanding of the nuclear measurement techniques discussed during the theoretical lectures, as well as to acquire the practical applications of these techniques. The participants of the laboratory practice get an inside view of the fundamentals of gamma-ray spectrometry based on semiconductor detectors, become acquainted with its important devices and learn the basic steps of the evaluation of gamma-ray spectra.

The fundamental device to be used during the laboratory practice is an HPGe (High Purity Germanium) semiconductor detector, which can be used to identify gamma-ray emitting isotopes present in different samples, and to determine the *absolute* and *specific activity* of these isotopes. The practical significance of gamma-ray spectrometry lies in the fact that it can be applied in several fields to solve analytical or nuclear physical problems which are in connection with gamma-ray emitting isotopes. In nuclear physics studies, gamma-ray spectrometry is most commonly used to determine the lifespan and energy of the energy levels of atomic nuclei, to explore the decay schemes of isotopes, to measure the value of the internal conversion coefficient, to study gamma-gamma angular correlation, etc.

The areas of application with direct *practical purposes* are neutron activation analysis; medical, industrial and agricultural nuclear-related studies for the analysis of natural and artificial radioisotopes; and solving problems of environmental and radiation protection which can be studied with gamma-ray spectroscopic measurements.

Participants of the gamma-ray spectrometry laboratory practice can learn about the following:

- observation of the interactions between gamma radiation and matter
- construction of the gamma-ray spectrometer, and the spectroscopic characteristics of the individual components
- application of the signal processing electronics of HPGe detectors in gamma-ray spectrometry
- quantitative evaluation of gamma-ray spectra
- processing measurement data and estimating their uncertainty

2. Theoretical summary

Photoelectric effect, scattering, pair production, emission and absorption:

The alpha and beta decay of atoms, nuclear fission, and nuclear reactions frequently lead to an excited state of a daughter nucleus. The atomic nucleus produced during a nuclear process returns to its ground state from an excited state by the emission of one or more gamma photons. The energy, intensity and angular distribution of the gamma photons emitted during the decay of a radioactive atomic nucleus carries information about the internal structure of the radiating nucleus. An atomic nucleus can have several de-excitation processes, which are usually depicted using the so-called *decay scheme* (Figure 1). In Figure 1 the energy levels of an atomic nucleus, the atomic mass of which is *A* and the atomic number of which is *Z*, are depicted on the vertical axis, while the atomic number is represented on the horizontal axis.
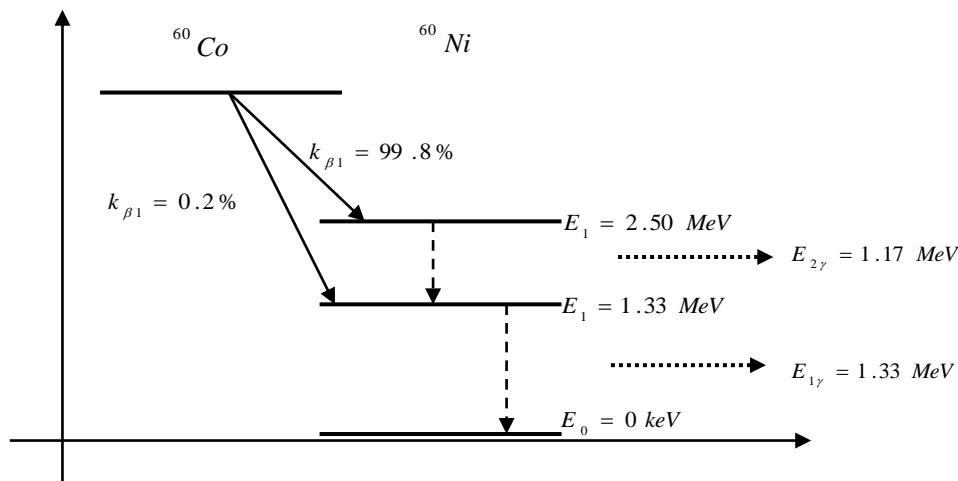

Figure 1. The decay scheme of ^{60}Co

Different transition probabilities, called the emission frequency of the specific beta or gamma emission, belong to different decay paths. The frequency values are nuclear constants characteristic of a specific atomic nucleus, and yield the number of cases in which the nucleus emits a beta particle or gamma photon with high probability, if 100 of this given atomic nucleus decay.

The interaction between gamma rays and matter can be characterized by three fundamental processes: the **photoelectric effect**, **Compton scattering** and **pair production**. These three basic physical processes have already been thoroughly analysed in other theoretical courses; therefore, only a short overview is given in this description.

During the **photoelectric effect** an X-ray photon transfers its total energy to one of the bound electrons of an atom, which thus becomes a free electron, while an electron-deficient state is created in the electron shell. As a result of the photoelectric effect occurring in the detector material, the energy of the electrons present in the semiconductor will be sufficient so that they can take part in the electrical conduction process. The cross section of this phenomenon can be provided by using formula (1) below, where Z is the atomic number of the material, and N is its atomic density:

$$\sigma_f \sim NZ^5 \left(E_\gamma\right)^{-3.5} \qquad (1)$$

During Compton scattering, the photon transfers only a part of its energy (E_γ) to the free electron or to the atomic electron, the binding energy of which is little compared to energy E_γ. In this process, the energy and the direction of propagation of the incoming photon change. The magnitude of the energy of the scattered photon is expressed by formula (2), where $0° < \vartheta < 180°$ is the angle enclosed by the direction of propagation of the scattered photon and the direction of the primary photon, m is the rest mass of the electron, and c is the speed of light.

$$E_{\gamma'} = \frac{E_\gamma}{\dfrac{E_\gamma}{mc^2}\left(1 - \cos\vartheta\right) + 1} \qquad (2)$$

The cross section of the process can be given by using formula (3), known as the Klein-Nishina formula.

$$\sigma_{KN} \sim \frac{NZ}{E_\gamma} \ln\left(\frac{2E\gamma}{mc^2} + 0.5\right) \qquad (3)$$

Depending on the value of angle ϑ, the energy of the electron knocked in the Compton scattering process falls in a well-defined energy range, the consequence of which is the appearance of the Compton edge and the Compton plateau. For example, the energy of the Compton edge belonging to the 1333 keV photon produced during the decay of ^{60}Co is 1119 keV.

In the process of **pair production** a gamma photon can be converted into an electron-positron pair in the electric field of an atomic nucleus of the detector material, if the energy of the photon is higher than $2mc^2 = 1.022$ MeV. If the condition $E_\gamma > 1.022$ MeV is met, i.e. the energy of the photon is higher than the sum of the rest masses of the two particles, then the remaining energy of the photon is spent on the kinetic energy of the electron and of the positron. The positron later combines with an electron, which results in **annihilation.** In this process two 0.511 MeV photons

appear in the detector. The cross section of the pair production process is proportional to expression (4) below:

$$\sigma_p \sim NZ^2\left(E_\gamma - 2mc^2\right) \tag{4}$$

The result of the three fundamental interaction processes discussed above is the absorption of the gamma rays, the effect of which on the intensity of a gamma beam can be described by formula (5), where μ is the *absorption coefficient*, x is the thickness of the absorbing material, I_0 is the initial intensity, while I is the intensity of the beam exiting the absorbing layer.

$$I = I_o e^{-\mu x} \tag{5}$$

The semiconductor detector materials most frequently used are Ge and Si; therefore, the cross section of the three fundamental physical processes discussed above are given for these materials as a function of photon energy in Figure 2.
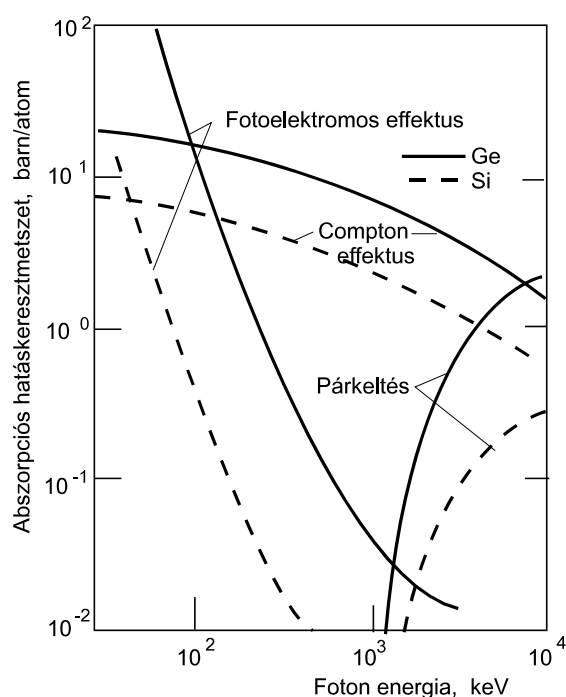

Figure 2. The changes in the cross sections of the fundamental
interactions between photons and atoms as a function of
photon energy in the case of Si and Ge.

It can be observed that the cross section of the photoelectric effect and pair production changes by several orders of magnitude, as opposed to the cross section of Compton scattering. The result of all three processes is the appearance of electrons in the detector material, the energy of which is sufficient so that they can take part in electrical conduction. By collecting the charge carriers

created in this way, a voltage or a current pulse, the amplitude of which is proportional to the energy of the absorbed gamma photon, appears on the electrical detector output. The task of the electronic and analogue-digital converter units of the spectrometer is to quantify the parameters of these pulses, and thus to display the energy distribution of the detected gamma-ray spectrum.

3. Instruments used in gamma-ray spectrometry

Detectors

Two types of semiconductor detectors are widespread in nuclear spectroscopy: single crystal Ge and Si detectors. Si detectors are primarily suitable for measuring beta particles and heavy charged particles. In single crystal Ge detectors approximately 3 eV absorbed energy is needed for an electron-hole pair to form. This value is approximately one tenth of the energy necessary for the same process in gas-filled detectors, and it is one hundredth of the energy needed in the case of scintillation detectors. Therefore, by the transfer of a given amount of energy, a significantly greater number of charge carriers are created in semiconductor detectors than in the two other types of detectors. Since the relative fluctuation in the number of charge carriers is significantly lower when there are more of them, the determination of the photon energy absorbed by the detector material becomes much more accurate. As a result, a considerably better energy resolution can be achieved with semiconductor detectors than with other types of detectors. The efficiency of gas-filled detectors, the density of which is low or which contain relatively little detector material, is low for gamma radiation, while the higher atomic number and higher density of Ge results in a higher efficiency, which makes it ideal for detecting gamma radiation. The atomic number of Si is lower; therefore, it is primarily used to detect low-energy $(3 - 60 \text{ keV})$ gamma radiation and X-rays.

The cause of the metrological characteristics discussed above can be explained with the solid-state physical processes taking place in semiconductors. In a semiconductor single crystal, the highest energy level of an atom which is completely filled with bound electrons is the so-called *valence band*, while the energy band of those electrons that are not bound to the atoms and can move freely in the solid semiconductor is called the *conduction band*. The band between these two bands is known as the *forbidden band* and it does not contain any electron states.

The width of the forbidden band in semiconductor materials is 1-2 eV. As a result of radioactive radiation, heat or light, some of the electrons of the valence band can move to the conduction band and thus can take part in electrical conduction. If a gamma photon interacts with the electrons of the crystal, it transfers its energy to them; thus, the electrons move from the valence band to the conduction band. The excited electrons leave behind an electron-deficient state in the valence band.

In order to create such an electron-hole pair, approximately 2.8 eV is needed in Ge, while 3.6 eV in Si.

The approximately 1000 V/cm electric field strength created by the voltage supplied to the detector results in a unidirectional flow of charge carriers into the electrodes of the detector. The electric circuits further transform the pulse consisting of the charges created in this way. It is important to note that the specific resistance of the applied semiconductor materials is approximately 10^8 Ωcm, since otherwise the noise originating from their natural electric current would be excessively high. Since electrons can move to the conduction band by obtaining their energy randomly from thermal energy of the environment, they can amplify the current of the spectrometer without the actual detection of gamma photons; consequently, this phenomenon results in noise. In order to reduce *thermal noise*, semiconductor detectors have to be operated at low temperature (approximately 77 K), using liquid nitrogen cooling. Today, semiconductor detectors equipped with cooling systems using the Peltier effect exist, as well as such that operate at room temperature (SDD = Silicon Drift Detector). Depending on the purpose of use, several unique solutions were developed for the technical and geometric construction of HPGe detectors. The geometric arrangements most frequently used can be seen in Figure 3. For further details, see the corresponding references and the material of the course *Nuclear Measurement Techniques*. In this laboratory practice, we are going to use a p-type coaxial detector.
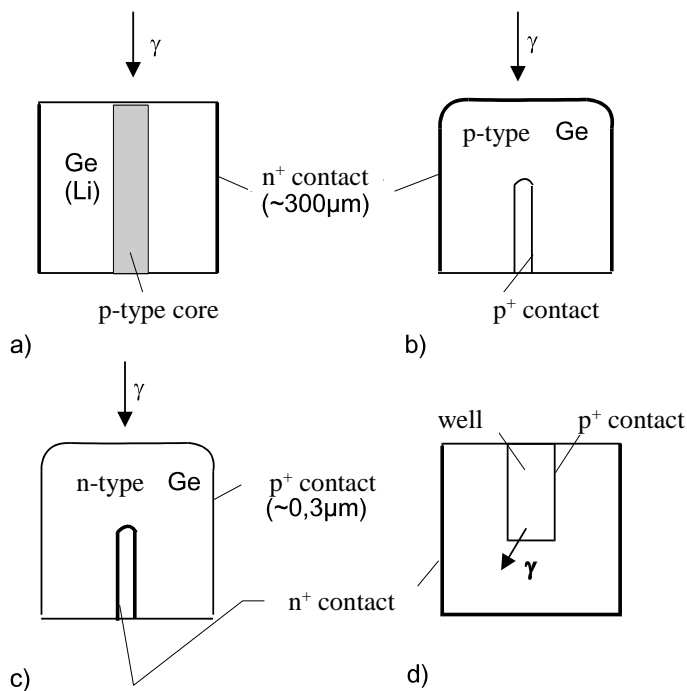

Figure 3.   Ge-type detectors:

a. open-ended coaxial Ge/Li

b. closed-end p-type coaxial

c. closed-end n-type coaxial

d. well-type.

Electronic signal-processing units

The specific nuclear detection task determines which electronic units of a gamma-ray spectrometer are applied. The task of the **pre-amplifier** is fitting between the detector and the main amplifier and the amplification of the signal before transmitting it in a way that the signal to noise ratio is as favourable as possible. The **main amplifier** is required to be highly linear and stable in time. The **baseline restorer** moderates the degree with which the baseline drops (with which the amplitude of a signal changes) in the case of high counting rates. The **expander amplifier** makes the expansion of certain parts of the spectrum possible, if a more detailed analysis of the structure of the spectrum is needed. The **stretcher** provides the input of the analyser (ADC: analog-to-digital converter) with an electronically more favourable signal. The **pulser** is a pulse generator with stable frequency and amplitude, which is used for analysing signal shapes and for automatic dead time correction. **Multichannel pulse amplitude analysers** are usually used with two different types of ADC: the Wilkinson-type is the slower one, while the faster one is based on the successive approximation of signal analysis. The **high-voltage power supply** provides the voltage necessary for the operation of the detector (2000 – 5000 V). In the case of semiconductor detectors high stability is not a requirement, but a low level of electronic noise is. The **low voltage power supply** ($\pm 6, \pm 12, \pm 24$ V) is the power source of the different electronic units (amplifiers, etc.). In this laboratory practice a DSP signal processing unit is used, which, apart from the functions listed above, performs the digitization of analog signals, and loads the individual channel contents directly into the PC memory.

4. The evaluation of gamma-ray spectra

Figure 4 depicts the theoretical shape of the spectrum of mono-energetic gamma radiation. The appearance of the full-energy peak is primarily due to the photoelectric effect; therefore, it is also referred to as the photopeak. The so-called annihilation peak, which appears at 511 keV, is either the result of the pair production process or originates from a positive beta-decaying isotope. The backscatter peak is the consequence of the detection of the photons scattered off the housing of the detector, or the inner wall of the shielding of the measuring station. In gamma-ray spectra it is possible to reduce the magnitude of the continuous background below the peaks, and thus the limit of detection of a given isotope, by positioning the scattering surfaces farther and by reducing the atomic number of their material. The backscatter, annihilation, etc. peaks are superimposed on the so-called Compton region formed as a result of the Compton interaction.

The fundamental aim of the evaluation of the spectrum is the determination of the *full-energy peak* area. In order to do this the following steps need to be taken:

- energy calibration of the spectrum

- search for peaks

- identification of the isotopes belonging to the peaks using an isotope library

- mathematical separation of the overlapping peaks and the fitting of mathematical functions to the spectrum

- calculation of peak areas

- calculation of the activity and specific activity of the isotopes belonging to the individual peaks.

The above tasks can be performed with the **Genie-2000** measurement control software, the short guide to the basic functions and directions for use of which can be found in the description attached to this one.
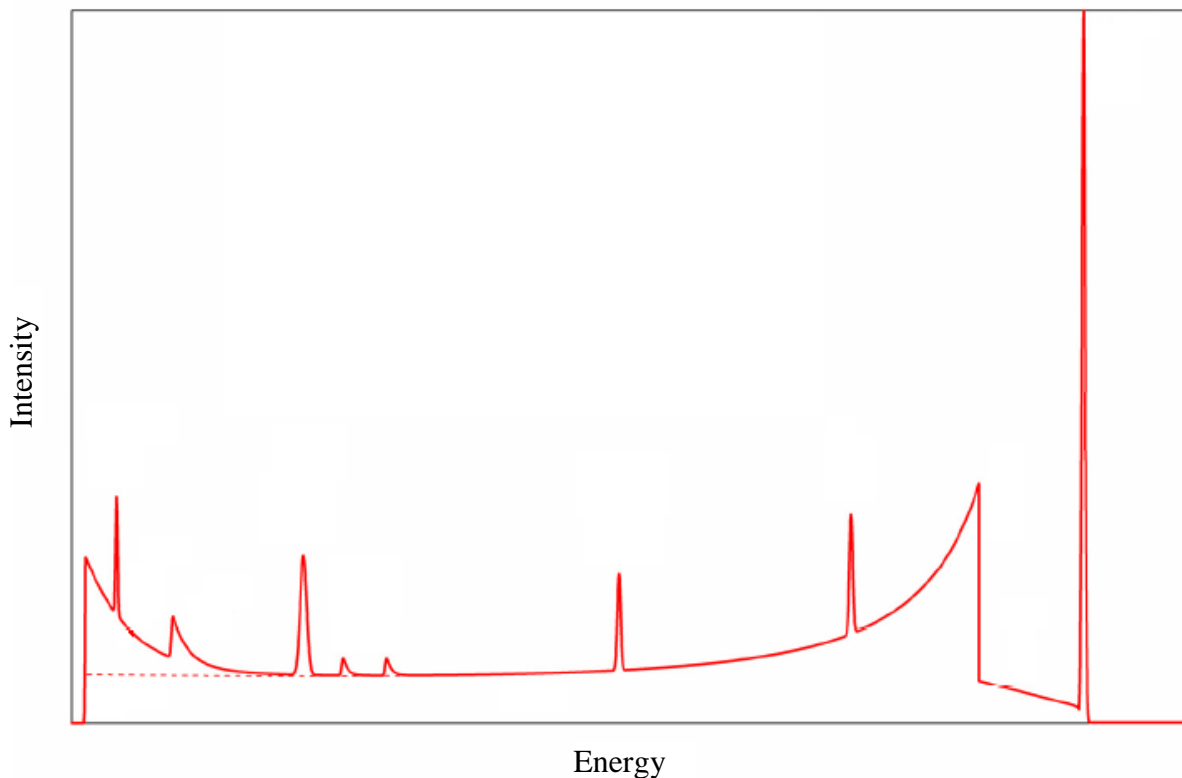

Figure 5.   The structure of a gamma-ray spectrum taken with an HPGe detector.

The necessary terms for evaluating gamma-ray spectra, and their calculation

Several fundamental parameters need to be defined so that gamma-ray spectrometers can be quantitatively characterized. The energy resolution of a detector is a parameter which is dependent

on the energy of the gamma photons, and which provides the full width at half maximum (FWHM) of a gamma peak at a given energy as a function of the energy corresponding to the centre of the peak. The gamma peaks can mathematically be described with a Gaussian function in accordance with formula (6). The widening of the curve can be characterized with the width of the peak belonging to half of its maximum value (FWHM).

$$y_i = \frac{y_0}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(E - E_0)^2}{2\sigma^2}\right) \tag{6}$$

There are several reasons for the widening of the peaks, the most significant of which are the physical processes taking place in the detector, and the noise generated by the electronic units. In the case of a given detector, the value of f is dependent on gamma energy (it gets better if gamma energy increases) and to some extent on counting speed (it gets worse if the counting rate increases). In the case of Ge detectors, $\Delta E \approx 1.8 - 2.7$ keV at 1333 keV (^{60}Co) gamma energy.

The energy-dependence of the full width at half maximum is affected by numerous factors, as a result of which the relationship between the FWHM and the energy of the detected gamma photons is as given below. Further information on the processes affecting the value of the FWHM can be found in Reference [1] and [2]. The Genie-2000 software approximates the energy-dependence of the full width at half maximum with formula (7).

$$FWHM = a + b\sqrt{E} \tag{7}$$

where k and r are constant, and E is the energy of the gamma photons.

The value of the **absolute** or **full-energy peak efficiency** represents the number of gamma photons the detector records in the full-energy peak out of all the gamma photons emitted from the source of radiation at a given energy. The mathematical definition of efficiency can be given with formula (8), where N is the area of the full-energy peak, which can be obtained by detecting the gamma radiation originating from a source of radiation, the activity of which is A at the time of detection; t_m is the duration of the measurement; and k is the value of gamma abundance.

$$\eta = \frac{N}{t_m A k} \tag{8}$$

The value of **absolute efficiency** decreases as the energy of the gamma rays increases, it increases if the volume of the detector increases, and it is significantly affected by the geometry of the measurement: the distance between the source and the detector, and the shape, size and material of

the source. The companies which produce semiconductor detectors provide the so-called **relative efficiency**, which refers to the 1333 keV line of a ^{60}Co point source placed 25 cm away from the detector, as given in formula (9):

$$\eta_{rel} = \frac{\eta_{Ge}}{\eta_{NaI}} \quad , \quad (9)$$

where $\eta_{NaI} = 1.2 \cdot 10^{-3}$ is the absolute full-energy peak efficiency of a 75x75 mm NaI(Tl) scintillation crystal in the geometry described above.

Correction for decay during the measurement period

If the half life of the isotope to be studied is short compared to the duration of the measurement period, i.e. it is comparable with the measurement time of the sample, the decays occurring during the measurement period need to be taken into consideration when determining the activity. Formula (10) can be given based on the time dependence of the radioactive decay, where λ is the decay constant of the isotope, t_m is the duration of the measurement, N_0 is the activity of the radioactive specimen at the start of the measurement, and N_m is the activity measured during the whole duration of the measurement.

$$N_0 = \frac{N_m}{\int_0^{t_m} e^{-\lambda t} dt} = \frac{N_m \lambda t_m}{1 - e^{-\lambda t_m}} \quad (10)$$

Corrections due to true coincidence and sample composition

In the case of practical gamma-ray spectroscopy measurements the application of two further corrections may be necessary. One of these phenomena is *true coincidence*, which occurs if isotopes emitting several photons by *cascade decay* within the dead time of the spectrometer are present in the sample to be studied (examples include ^{60}Co and ^{152}Eu). The probability of this effect increases as the volume of the detector increases, and the distance between the sample and the detector decreases, but it is independent of the activity of the sample. As a result of true coincidence, *sum peaks* appear in the spectrum, which are formed of the sum of two real full-energy peaks; at the same time, the area of the full-energy peaks decreases. The correction of true coincidence is usually a complicated calculation, for which the Genie-2000 software used during the laboratory practice is prepared.

During the study of high-volume samples, *self-absorption* occurring in the sample can cause significant changes in intensity. This takes place if the photons, which are emitted from parts of the

sample farther from the detector, can only reach the detector crystal by passing through the material of the sample. In this case the number of photons detected decreases depending on the absorption properties of the sample. Ignoring this phenomenon when measuring low-energy (approximately below 150 keV) gamma rays can cause significant errors. In order to determine the correction for self-absorption, the sources used in efficiency calibration need to be prepared with isotopes mixed into them, the absorption properties of which are similar to those of the sample. Knowing the composition of the sample, another solution can be the estimation of the extent of correction with theoretical calculations.

Peak area calculations

In the laboratory practice, the Genie-2000 analysis software is used, which automatically calculates the peak areas and their errors according to the algorithm below.

$$N = \sum_{i=a}^{b} \left(y_i - (b - a + 1) \frac{y_a - y_b}{2} \right)$$

$$\sigma_N = \sqrt{N + 2B}$$
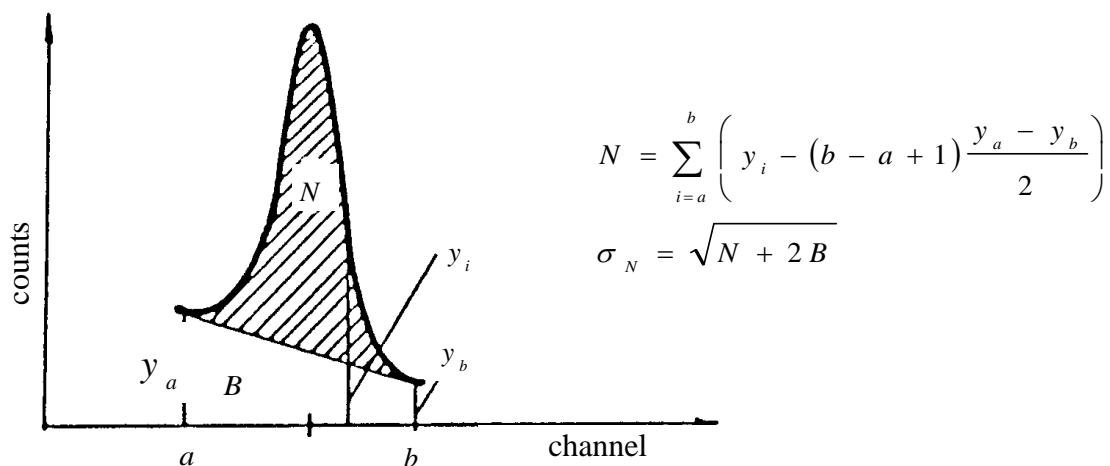
Figure 6. The elements of the evaluation of the gamma peaks, where N is the net peak area, and σ_N is the statistical error of the peak area.

With the analysis software, groups consisting of overlapping peaks can also be evaluated. In this case, a complex function shape consisting of several mathematical functions is fitted to the corresponding part of the spectrum, from the result of which the net area below the peaks can be determined.

Measurement tasks

1. Energy calibration

In order to perform energy calibration, place standard point sources (^{60}Co, ^{137}Cs) which emit known gamma energies in front of the detector. Record a gamma spectrum. Knowing the energies, determine the gamma energy – channel number function by searching for the position of the full-energy peaks. In practice, usually either a first-degree or a quadratic function is fitted to the measured data pairs. For performing this task, use the menu item for energy calibration of the Genie-2000 software (menu item **Calibration**). In the simplest case, let the two known calibration energy values be E_1 and E_2, and the corresponding channel numbers be Ch_1 and Ch_2. Supposing that the device is linear, the software calculates the slope of the calibration line based on the straight line passing through the two points given below.

$$ m = \frac{E_2 - E_1}{Ch_2 - Ch_1} \left[\frac{keV}{chan} \right] \tag{11} $$

where m is the slope of the energy calibration line, which provides the energy value of an interval between two channels in the case of a given amplification. It is practical to rearrange equation (11) into the following form, where b is the intercept of the calibration line:

$$ E = m\,Cs + b \tag{12} $$

In order to perform the energy calibration, select menu item **Calibrate/Energy Only Calibration**, where the energy and the channel number of the maximum of the peak corresponding to the individual lines of the isotopes used for calibration need to be entered manually. In order to perform the task described above, use the data corresponding to the calibration gamma sources listed in Table 1. Measure the gamma spectrum of a few standard radiation sources, which you receive from the laboratory instructor. Check the calculated energy calibration curve by using the lines, the energy of which is known, of the sources received from the laboratory instructor. Perform the measurement in the following way: change the individual standard sources during the measurement in order to obtain mixed spectra, which contain the lines of all the measured isotopes. Choose the time of measurement so that the statistical error of the gamma peak areas will not be higher than 1-3%. Pay attention to the length of dead time as well, which you can affect by the appropriate choice of the distance between the sample and the detector: 0, 10, 50, 150 mm. Dead time should not be longer than 1-2% during the measurement.

Task 1. Energy calibration					
Isotope		**Energy (keV)**	**Channel number**	*m*	*b*
1.	^{133}Ba	81.0			
2.	^{57}Co	122.1			
3.	^{133}Ba	276.4			
4.	^{133}Ba	356.0			
5.	^{137}Cs	661.7			
6.	^{60}Co	1173.2			
7.	^{60}Co	1332.5			
Energy of the lines of known radiation sources					
	Isotope	**Energy (keV)** (based on the table)		**Energy (keV)** (based on energy calibration)	
1.	^{241}Am				
2.	^{22}Na				
3.					
4.	^{152}Eu				
5.					
6.					

Note down the data related to this task in the table belonging to the subtask. You find an acrylic (plexiglass) stand and a plexiglass sample holder, on top of which the standard sources need to be placed, in the shielded measurement chamber. By changing the height of position of the plexiglass sample holder, different sample-to-detector distances can be set. The sample-to-detector distances corresponding to the individual positions are indicated at each position. You can find the parameters calculated by the Genie-2000 software and the fitted calibration curve under menu item **Calibrate/Energy show**.

2. The determination of the energy resolution of the spectrometer

In order to perform this task, use the "mixed" spectrum with the known peaks recorded and stored in the previous section. Determine the value of the FWHM of the individual peaks, then plot the data. Fit the function $FWHM = a + b\sqrt{E}$ to the data as a function of energy.

Task 2. The determination of the energy resolution of the spectrometer				
Isotope	**Energy (keV)**	**FWHM (keV)**	*a*	*b*
1. ^{133}Ba	81.0			
2. ^{57}Co	122.1			
3. ^{133}Ba	276.4			
4. ^{133}Ba	356.0			
5. ^{137}Cs	661.7			
6. ^{60}Co	1173.2			
7. ^{60}Co	1332.5			

3. The determination of the absolute efficiency function of the detector

Place standard point sources of known activity and energy in front of the detector in a way that dead time is always less than 5% during the measurement. Measure the gamma spectrum of the individual isotope sources. Since efficiency is dependent on the geometrical arrangement, always use identical sample-to-detector distances during the measurements.

Evaluate the measured spectra with the Genie-2000 program and calculate the integral of the full-energy peak (N), then determine the values of efficiency (η) at the energies of the measured peaks by using formula (8): $\eta = N/t_m A k$.

Task 3. Determination of the energy dependence of the absolute efficiency of the detector							
Height of position of the sample holder:					mm		
Isotope		t_m (s)	A (Bq)	Date	Gamma energy (keV)	k	$\eta_{calculated}$	η_{fitted}
1.	^{133}Ba				81.0			
2.	^{57}Co				122.1			
3.	^{133}Ba				276.4			
4.	^{133}Ba				356.0			
5.	^{137}Cs				661.7			
6.	^{60}Co				1173.2			
7.	^{60}Co				1332.5			
The values of the fitted efficiency parameters							
a		b		c		d	

Plot the values of the calculated efficiency ($\eta_{calculated}$) as a function of energy on a log-log graph. It is practical to fit a polynomial function of the form (13) to the measured efficiency data, where η is the value of the efficiency calculated according to the table above at energy E.

$$\ln \eta = a + b \ln E + c (\ln E)^2 + d (\ln E)^3 \qquad (13)$$

Determine parameters *a, b, c,* and *d* from the fitting. Knowing the efficiency, calculate the activity of the detected isotopes. Determine the efficiency function of the detector for the geometry of the point source corresponding to the given distance.

4. The determination of the activity of a radioactive point source

Determine the activity of a source provided by the laboratory inspector. The calculation of the activity can be performed based on formula (14) derived from equation (8), where *N* is the net peak area [imp], t_m is the duration of the measurement of the sample, and *k* is the gamma abundance of a given gamma-ray line.

$$A = \frac{N}{t_m \eta k} [Bq] \qquad (14)$$

Estimate the error of the result by using formula (14), where σ_A is

$$\frac{\sigma_A}{A} \approx \frac{\sigma_N}{N} = \pm \frac{(N + 2B)^{1/2}}{N} \qquad (15)$$

Task 4. The determination of the activity of a radioactive point source								
Height of position of the sample holder: mm								
Isotope		t_m (s)	N (cps)	η	**Energy of the gamma-ray line (keV)**	k	$A_{calculated}$ (Bq)	σ_A (Bq)	A_{real} (Bq)
1.	^{152}Eu				121.8	28.6			
2.					344.3	26.5			
3.					964.1	14.6			
4.					1408.0	21.0			

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Questions

1. List five gamma-decaying isotopes and their mode of decay.

2. List the important interactions between gamma-rays and the atoms of matter, and describe their characteristics.

3. What is the meaning of the decay scheme of radioactive isotopes?

4. How does the HPGe detector used for the detection of gamma radiation work?

5. Describe the construction of a gamma-ray spectrometer, the functions of the individual units, and its most important metrological characteristics.

6. What metrological significance does the geometric shape of the gamma radiation source have, as far as efficiency and self-absorption are concerned?

7. Why is the energy calibration of gamma-ray spectrometers necessary, and how is it performed?

8. What does energy resolution mean in gamma-ray spectroscopy, and how does the resolution of an HPGe detector as a function of energy change?

9. What does the absolute efficiency of the spectrometer mean, and how can it be determined for a point source?

10. How can background radiation be taken into consideration during the evaluation of gamma-ray spectra?

Data of standard gamma radiation sources used for calibration					
Isotope	**Energy of the gamma line (keV)**				
	Yield of the gamma line (%)				
²²Na	1274.53				
	99.95				
⁵⁷Co	122.06	136.47			
	85.60	10.68			
⁶⁰Co	1332.50	1173.24			
	99.99	99.97			
¹³³Ba	356.02	81.00	302.85	383.85	276.40
	62.05	34.06	18.33	8.49	7.16
¹³⁷Cs	661.66				
	85.1				
²⁴¹Am	59.54	26.345			
	35.9	2.40			
¹⁵²Eu	121.8	344.3	778.9	1408.0	1112.1
	28.6	26.5	12.9	21.0	13.6
	1085.9	964.1	867.4	778.9	244.7
	10.2	14.6	4.3	12.9	7.6
	411.1	443.9	919.3	1089.7	1212.9
	2.2	2.8	0.43	1.73	1.4
	1299.1	1457.6	1084.0	1005.3	488.7
	1.62	0.50	0.25	0.65	0.42