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1 Measurement of a Gamma-Ray Spectrum

1.1 The purpose of the experiment

To investigate some properties of a NaI detector.
To determine the energy of unknown gamma radiation.
To determine the nuclide that gives rise to the gamma radiation.

1.2 Equipment

NaI detector with accessories, computer, solution of ^{152}Eu , source of ^{137}Cs , pure KCl or a mineral salt (approx. 60 g) and other sources in which the gamma-ray energies are to be determined, e.g. an old watch with luminous digits or an incandescent mantle.

1.3 Theory

Recapitulate the theory of the interaction of gamma radiation with matter, the functioning of the NaI detector, how data are stored in the computer and what kind of commands are necessary for the data collection and the following analysis.

1.4 Performance

1.4.1 Properties of the NaI detector

- a) Collect a spectrum of a ^{137}Cs source. Place the source about 5 cm above the opening of the detector, to make sure that the count rate is not too high. Note the distance between the source and the detector. Measure for 3 minutes and make a sketch of the spectrum. Store the spectrum.

Note that a spectrum from a source with only one gamma-ray energy consists of a peak (the photo peak or the full-energy peak) and a distribution on the low-energy side (to the left) of the photo peak. If there are several photo peaks in a spectrum, the studied radiation must contain several different energies. See figure 1.

The low-energy distribution to the left of the photo peak in figure 1 originates from gamma quanta, which have collided with electrons in the detector crystal or in the lead shielding. The collision takes place in such a way that only part of the original energy of the gamma quantum is absorbed in the detector. This kind of collision is called Compton scattering (named after A H Compton, an

American physicist who first studied the process) and the low-energy distribution is the so-called Compton distribution. The Compton distribution always forms a background to the left of the photo peak with which it is associated.

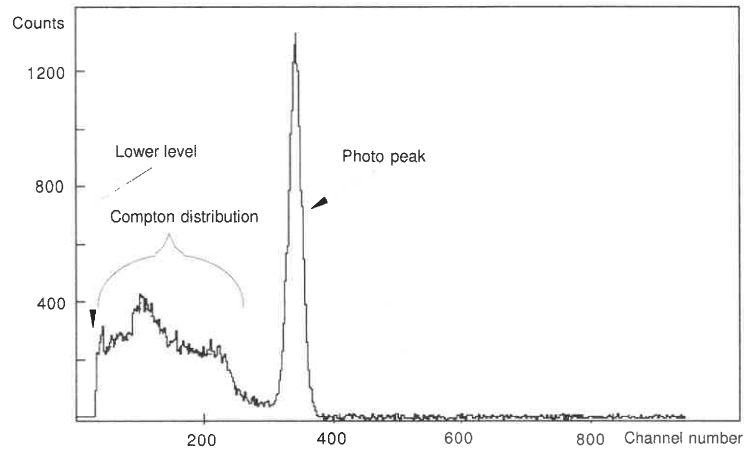


Figure 1.

Note in figure 1 that there is always a discriminator setting, which rejects the most low-energetic gamma quanta and the electronic noise. The discriminator setting can be adjusted with the knob on the amplifier box, but should not be changed during a measurement.

Note in your sketch of the ^{137}Cs spectrum where the photo peak, discriminator level and Compton distribution are situated.

- b) Record a spectrum of the ^{152}Eu solution, which is placed in the opening above the detector. The measuring time is chosen to be about 6 minutes. The spectrum is stored for later use in the energy calibration routine.
- c) Record a spectrum of KCl or of the mineral salt. The mineral salt contains KCl, and thus ^{40}K , which is a naturally occurring radioactive isotope. Measure for 15 minutes and then make a sketch of the spectrum. Compare with the background spectrum. Save the spectrum.
- d) Record a background spectrum, i.e. collect a spectrum without a source. The measuring time is 20 minutes. Don't forget to remove all sources close to the detector. Save the background spectrum. Compare with the ^{40}K spectrum in c.
- e) All recorded spectra in a - d are copied to the floppy disc belonging to each individual computer according to instructions given earlier.

1.4.2 Energy calibration of a gamma-ray spectrum

To perform any of the analysing procedures described below, one must first start the analysing programme on the respective computer. This is done by first typing CD DAS in order to change to the correct directory. Then type DAS, which loads the analysing programme DAS, which is exactly the same programme as used for the data collection. For the analysis, use only the commands listed on the distributed stencil. Alternatively one can use the function keys for the most common commands.

An explanation of the commands and the function keys can be obtained on the screen by the command **H**elp or in WinDAS User's Guide chapter 4.

Before a spectrum can be analysed the spectrum must be read into primary memory. This is done with the command **F**ile **O**pen.

1.4.2.1 The relation between the channel scale (the channel number) and the energy of the radiation

Manual method

Determine the channel position of the photo peak in the spectrum of ^{137}Cs by using the centroid routine, which is prepared by first placing the cross of the lower marker on the left edge of the photo peak and the cross of the upper marker on the right edge of the same peak. This is most easily done by using the right and the left button of the mouse. See figure 2.

Now use the command **C**alculate **C**entroid, which gives the channel position of the centre of mass of the photo peak. Zero the spectrum on the screen (**F**ile **C**lear) and read the ^{40}K spectrum. Repeat the same procedure for the photo peak in the ^{40}K spectrum. Note that the number of pulses and the number of pulses per second in the photo peak are also given.

Draw a diagram of the energies of the two photo peaks as a function of the corresponding channel position, i.e. the energy along the vertical axis and the channel number along the horizontal axis. The energies of the gamma quanta of ^{40}K and ^{137}Cs are 1.46 MeV and 0.66 MeV, respectively.

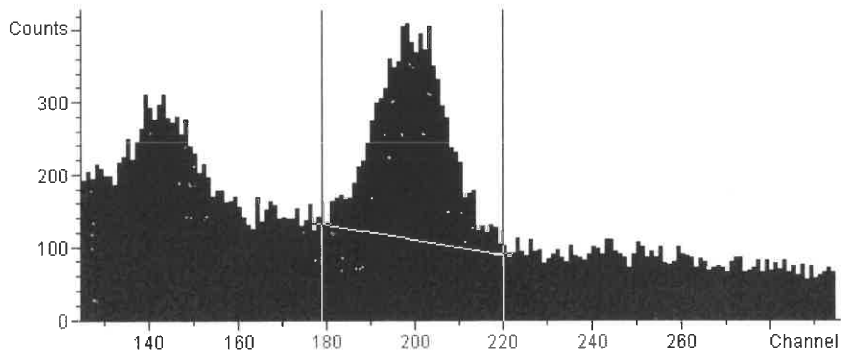


Figure 2.

Since the energy is very close to a linear function of the channel number you have now obtained an energy calibration. This means that each channel position corresponds to a definite energy.

Draw a straight line through the calibration points. Use the calibration to determine the size of the energy region (energy window) of your spectrum, by reading from the diagram the energies which correspond to the beginning and the end of the spectrum. A suitable energy window is in most cases about 0.07 - 2.00 MeV.

The energy window is:

The calibration routine of the computer

The programme WinDAS contains a calibration routine, which simplifies the energy calibration of spectra with unknown gamma energies. One uses a spectrum with at least two photo peaks with known gamma energies.

The spectrum of ^{152}Eu contains several peaks whose energies are well known. See figure 3. One may choose for energy calibration the two peaks which correspond to the energies 0.344 and 1.41 MeV. Start by reading the ^{152}Eu spectrum.

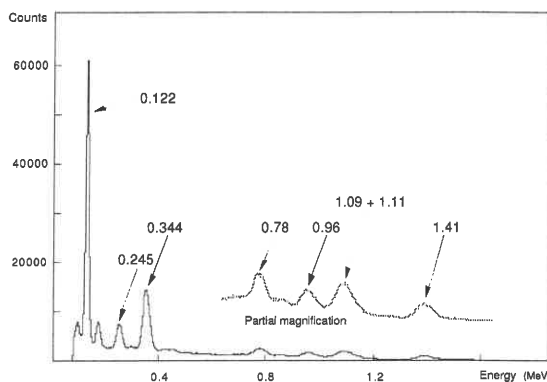


Figure 3. ^{152}Eu spectrum.

Each calibration peak is assigned an energy value. This is done by first determining the channel position of the peak with the command **C**alculate **C**entroid (see above) followed by the command **C**aLibrate **E**nergy. Repeat the same procedure for the photo peak that has the energy 1.41 MeV.

The spectrum is now calibrated, which can be seen on the x-axis where the channel scale has been replaced by an energy scale. Save the spectrum with a new name (**F**ile **S**ave). The energy calibration will from now on follow with the spectrum if the spectrum was saved after a completed calibration. If one thinks that the calibration was not satisfactory it can be repeated at any time by first removing calibration with **C**aLibrate **R**emove and thereafter repeat the calibration procedure as above.

The energy calibration can now be used to calibrate earlier recorded spectra from the ^{137}Cs source, KCl and the background. Read the spectrum that is to be calibrated and then **C**alculate **F**rom file.

Now determine with the help of the centroid routine the energy of the photo peaks that are seen in the spectra. This is done as described earlier by placing the markers to the left and right of the photo peak and giving the command **C**alculate **C**entroid. This time the position of the peak is given in the energy unit MeV. Compare the obtained energies with the energies used in the manual calibration.

1.4.3 Determination of the gamma-ray energies of an unknown gamma source

- a) Collect a gamma-ray spectrum from an unknown source given to you by your teacher. Copy the spectrum to your floppy disc and read it into your computer.

As before your earlier calibration may be used to calibrate the unknown spectrum.

- b) Compare the gamma energies obtained with the decay schemes your teacher has distributed and answer the following questions.

1.5 Questions

Question 1. From which decay does the measured radiation originate?

Question 2. Which are the daughter nuclei of the decay you have studied in this laboratory exercise?

Question 3. From the decaying nuclei gamma radiation as well as beta radiation is emitted. Why cannot the beta radiation be detected in the NaI detector?

Question 4) From where does the background radiation originate? Is there any radioactive nuclide that can easily be identified?

Additional experiment:

Comparison of the detection efficiency of a GM tube and the NaI detector.

Put the source of ^{137}Cs at about the same distance from the GM tube as from the NaI detector earlier. Count the number of pulses with the counter of the GM tube. Use the same measuring time as with the recording of the spectrum of ^{137}Cs .

Add the number of pulses in the photo peak of the gamma spectrum by using the centroid routine and compare this sum with the number of registered pulses in the GM tube.

Conclusion:

.....

2 Absorption of Gamma Radiation in Different Materials

2.1 The purpose of the experiment

To investigate the absorption of gamma radiation in lead, aluminium, etc.
To determine the half thickness and the linear absorption coefficient.

2.2 Equipment

NaI detector with accessories, source of ^{137}Cs , 10-20 metal sheets of each material (the number and the thickness depend on the absorption ability of the material). The metal sheets are about 3-5 mm thick. A stand for the source and the metal sheets, micrometer, millimetre paper and lin-log paper.

2.3 Theory

The following equation is valid for the absorption of gamma radiation in matter

$$I = I_0 e^{-\mu x} \quad (1)$$

where

I_0	is the intensity of the radiation striking the absorbing material
I	is the intensity after the absorber
x	is the thickness of the absorber
μ	is the linear absorption coefficient of the material.

If the logarithm of equation (1) is formed one obtains

$$\ln I = \ln I_0 - \mu x \quad (2)$$

If equation (2) is compared with the equation of a straight line, $y = kx + m$, it is realised that equation (2) is a straight line in a coordinate plane with a linear x -axis and a logarithmic y -axis ($\log I$ -axis). The slope k of the line is given by

$$k = -\mu \quad (3)$$

The ability of a material to absorb radiation is often expressed in terms of its half thickness ($X_{1/2}$), i.e. the thickness which absorbs half of the intensity of the radiation. The half thickness can be related to the absorption coefficient μ according to equation (2):

$$\ln(I_0/2) = \ln I_0 - \mu X_{1/2} \quad (4)$$

If the half thickness is determined experimentally, μ can be calculated from equation (4):

$$\mu = \ln 2 / X_{1/2} \quad (5)$$

Alternatively, μ can be determined from equation (3) with the aid of the slope of the straight line (2). Both ways can be applied in the laboratory exercise.

2.4 Performance

In the experiment one can use either a horizontal or a vertical experimental set-up depending on the design of the radioactive source holder and the stand for the absorbing metal sheets. Figure 4 shows schematically the horizontal alternative.

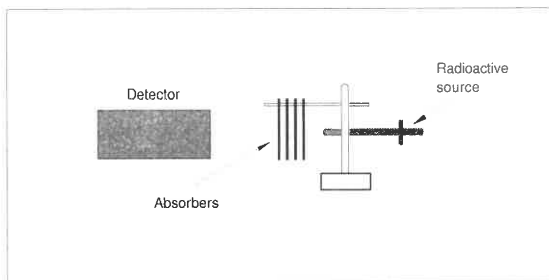


Figure 4.

A spectrum is collected for each absorber thickness. Choose several different absorber thicknesses, about 8. The measuring time is kept constant at about 30 seconds. Use the possibility to collect a spectrum for a predetermined time with help of the command **Acquire Preset Time**. Then determine the number of pulses in the photo peak of each spectrum (use the centroid routine **Calculate Centroid**). Fill in the area of the photo peak of each spectrum in the table below.

Thickness of absorber (mm)				
Number of counts				

Draw a diagram on a millimetre paper with the number of pulses on the vertical axis and the absorber thickness on the horizontal axis. Then draw a diagram on lin-log paper with the same choice of axes. Describe briefly the shape of the diagrams.

Since the intensity is proportional to the measured number of pulses, the diagram on the lin-log paper can be used directly to determine the half thickness. Calculate the absorption coefficient according to equation (4). The complete account of the calculation and the result is enclosed together with the answers to the questions below.

2.5 Questions

Question 1. Try to derive equation (5) from equation (4).

$$\ln(I_0/2) = \ln I_0 - \mu X_{1/2} \quad (4)$$

$$\mu = (\ln 2)X_{1/2} \quad (5)$$

Question 2a. Calculate the thickness of the lead shield needed to reduce the intensity to one thousandth of its initial value.

$$\mu_{Pb} = 1.22 \text{ cm}^{-1} \text{ for the gamma energy of 0.66 MeV.}$$

Question 2b. Repeat the calculation for aluminium.

$$\mu_{Al} = 0.208 \text{ cm}^{-1} \text{ for the gamma energy of 0.66 MeV.}$$

Question 2c. Repeat the calculation for air.

$$\mu_{air} = 0.000112 \text{ cm}^{-1} \text{ for the gamma energy of 0.66 MeV.}$$

Question 3a. Calculate the reduction of the intensity of the gamma radiation after the passage of 20 cm air.

Question 3b. Calculate the reduction of the intensity of the gamma radiation after the passage of 20 cm lead.

Question 4. In the experiment the intensity of the gamma radiation is measured by summing the number of counts in the photo peak. Why is not a window set over the whole spectrum to sum all counts in the spectrum?

3 The Efficiency of the NaI Detector

(Measurement of the activity of a ^{40}K solution)

3.1 The purpose of the experiment

To determine the efficiency of the NaI detector at different gamma-ray energies.

To determine the activity in a solution of ^{40}K .

3.2 Equipment

NaI detector with accessories, solution of ^{152}Eu for calibration, KCl, water and an empty standard jar.

3.3 Theory

The solution of ^{152}Eu is used to determine the efficiency of the detector at different gamma energies.

The gamma activity of a certain transition, i.e. the number of gamma quanta per second, is usually not equal to the activity of the source, i.e. the number of decays per second, since only a fraction of the decays may give rise to a specific gamma-ray transition. The decay scheme tells how big a proportion of all decays results in a certain gamma transition. Figure 5 shows a spectrum of ^{152}Eu , and figure 6 a (simplified) decay scheme for ^{152}Eu .

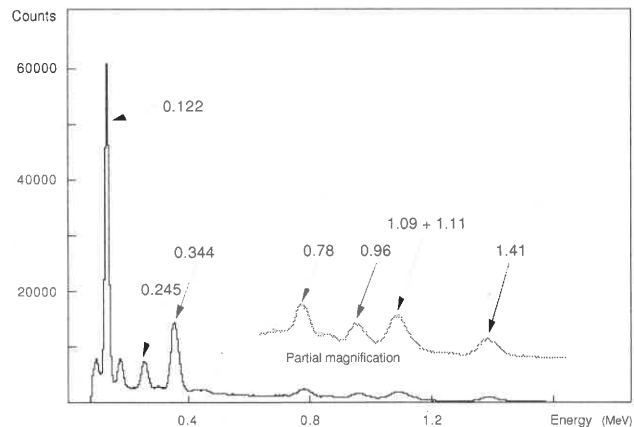


Figure 5. ^{152}Eu spectrum

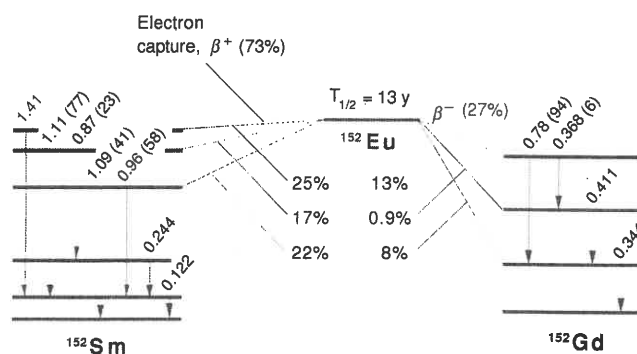


Figure 6.

For the efficiency calibration one uses the gamma transitions in the table below. The table gives the corresponding number of gamma quanta per decay of ^{152}Eu . The values in the table also contain a correction for deexcitation by electron emission (so-called internal conversion electrons).

Calibration lines in ^{152}Eu	
Energy (MeV)	Number of gamma quanta per decay
0.122	0.307
0.245	0.079
0.344	0.272
0.78	0.133
0.96	0.145
1.41	0.214

With the aid of the table it is possible to calculate the gamma activities for the different transitions.

Example: The calibration solution contains an activity of ^{152}Eu of 2000 Bq. The number of gamma quanta with the energy 0.344 MeV is then given by $2000 \cdot 0.272 = 544$ per second, i.e. the gamma activity for the 0.344 MeV transition is 544 Bq.

The activity for the calibration solution containing ^{152}Eu is:.....

The gamma activity for the 0.122 MeV transition is:.....

The gamma activity for the 0.245 MeV transition is:.....

The gamma activity for the 0.344 MeV transition is:.....

The gamma activity for the 0.78 MeV transition is:.....

The gamma activity for the 0.96 MeV transition is:.....

The gamma activity for the 1.41 MeV transition is:.....

By relating the gamma activity to the number of counts in the photo peak counted per second one obtains a measure of the efficiency of the detector at the corresponding gamma energy. This efficiency calibration can now be used to transform the registered number of counts per second to the actual gamma activity for other samples. With a knowledge of the decay scheme one can then determine the activity (number of decays per second) of an unknown sample.

The efficiency of the detector, k_{eff} , is thus determined by calculating the ratio between the number of gamma quanta per second, obtained from the photo peak, and the gamma activity for the corresponding transition.

In order to investigate if the efficiency of the detector is energy dependent, the efficiency determination is made at different gamma-ray energies.

If the calibration source and the sample with the unknown activity have different geometry or density, or are placed differently relative to the detector, sources of error are introduced in the efficiency calibration. In order to minimise these errors the calibration spectrum and the spectrum of the sample to be measured should be collected at as identical conditions as possible. The most important is the size of the sample and the placement relative to the detector.

The activity in a KCl solution can be calculated according to the following:

$$A = \lambda N \quad (1) \quad \text{Where } \lambda \text{ is the decay constant}$$

N is the number of mother nuclei

$$\lambda \text{ is obtained from } \lambda = \frac{\ln 2}{T_{1/2}} \quad (2) \quad \text{Where } T_{1/2} = 1.26 \cdot 10^9 \text{ year, is}$$

the half life of ^{40}K
for

N is calculated according to the following:

Suppose the mass of the sample = m (g)

The mass of KCl in the sample is then $m \cdot Y$, where Y is the weight percentage of KCl.

The number of potassium ions in the sample is equal to the number of KCl molecules:

$$N_K (=N_{\text{KCl}}) = \frac{m \cdot Y}{M_{\text{KCl}}} \cdot N_A \quad (3) \quad \text{Where } N_A = \text{Avogadro's number}$$

$(= 6.022 \cdot 10^{23} \text{ mol}^{-1})$
 M_{KCl} = mass of a mole of KCl

If $X = 0.0118 \%$ is the percentage of ^{40}K in naturally occurring potassium, then:

$$N = X \cdot \frac{m \cdot Y}{M_{\text{KCl}}} \cdot N_A \quad (4)$$

and consequently

$$A = \frac{N_A X Y m \ln 2}{M_{\text{KCl}} \cdot T_{1/2}} \quad (5)$$

3.4 Performance

3.4.1 Calibration of the efficiency of the detector

Collect a spectrum of the ^{152}Eu calibration solution and the background spectrum. A suitable measuring time is about 10 and 30 min, respectively, per spectrum. Copy the spectra to your floppy disc.

Before it is possible to determine the number of counts in the photo peak the contribution from other radiation sources (the background) must be subtracted. Subtract the background spectrum from the calibration spectrum by first reading the calibration spectrum and then giving the command **File Subtract**. The screen now shows the difference.

Determine the area of the different calibration peaks and write down the values in the table below. Complete the table and draw a calibration curve with the efficiency as a function of the gamma-ray energy, using the values from the table.

The activity of ^{152}Eu in the solution (Bq): Measuring time (s):

Energy (MeV)	Gamma activity (Bq)	No. of counts in the photo peak	No. of counts per sec in the photo peak	Efficiency (%)
0.122				
0.244				
0.344				
0.78				
0.96				
1.41				

What is the conclusion drawn about the energy dependence of the efficiency?

.....

.....

.....

3.4.2 Determination of the activity in a solution of KCl

Mix, in the standard jar, about 15 grams of KCl with water. Shake until the salt is dissolved.

Collect a spectrum of the solution. Measure for about 30 minutes. Subtract the earlier collected background. While the spectrum is being collected you can calculate the expected theoretical value for the activity.

The weight of the KCl salt (g):.....

The theoretical activity is:.....

Determine now the gamma activity in the solution from the photo peak area and the earlier determined efficiency. With the help of the decay scheme of ^{40}K in figure 7 the activity in the solution is calculated.

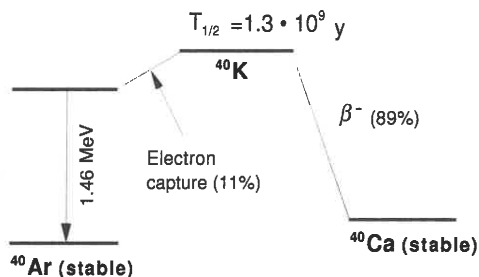


Figure 7.

4 The Half Life of ^{214}Pb

4.1 The purpose or the experiment

To determine the half life of the radioactive decay of ^{214}Pb .

4.2 Equipment

NaI detector with accessories, high-voltage power supply (about 5 kV), 2-4 m thin metal wire (diameter about 0.2 mm), holder and stand, a small plastic bag or plastic foil, calibration of source (^{152}Eu), millimetre paper and lin-log paper.

4.3 Theory

4.3.1 Radioactive decay

In radioactive decay the number of radioactive nuclei of an isotope varies according to the following equation:

$$N = N_0 e^{-\lambda x} \quad (1)$$

where N_0 is the number of mother nuclei at the time $t = 0$.
 N is the number of remaining mother nuclei after the time t
 λ is the decay constant, i.e. the probability per second that a nucleus will decay

If one takes the logarithm of equation (1) one obtains

$$\ln N = \ln N_0 - \lambda x \quad (2)$$

If equation (2) is compared with the equation of the straight line $y = kx + m$, it is realised that equation (2) is a straight line in a coordinate plane with a linear x -axis and a logarithmic y -axis ($\log N$ -axis). The following is valid for the slope k of the line:

$$k = -\lambda \quad (3)$$

$T_{1/2}$ is the half life, i.e. the time from $t = 0$ to the time when half of the original number of mother nuclei remains. This gives

$$\ln (N_0/2) = \ln N_0 - \lambda T_{1/2} \quad (4)$$

If the half life is determined experimentally, λ can be calculated from equation (4) as

$$\lambda = (\ln 2)/T_{1/2} \quad (5)$$

Alternatively, λ can be determined from the slope of the curve in the lin-log diagram. Both ways can be used in this laboratory exercise.

4.3.2 Collection and preparation of the activity

Since it is expensive and difficult to buy radioactive sources with half lives suitable for use in schools, we shall collect daughter nuclides of radon, which may occur in sufficient concentrations in many houses. The occurrence depends on the properties of the ground and on the building material of the house. Unventilated rooms close to or below ground level show the largest percentages of radon in the air.

The decay chain of ^{222}Rn consists of several different alpha decays, which means that the electron shells of the daughter nuclides often are only partially filled, i. e. positive ions have been formed. These can be trapped on a negatively charged wire, which has been stretched across the room. After the collection, the wire is wound tightly around a small piece of wood or paper and the activity can now easily be studied with a NaI detector. (Alternatively one can use a vacuum cleaner to collect the radioactivity which is stuck on dust particles in the air. This is done by placing a filter in front of the inlet of the vacuum cleaner.)

By studying the gamma quanta of ^{214}Bi , which is the daughter nucleus of ^{214}Pb , the half life of ^{214}Pb (see figure 8) can be determined. To understand the gamma spectrum the decay scheme of radon in figure 8 must be studied carefully.

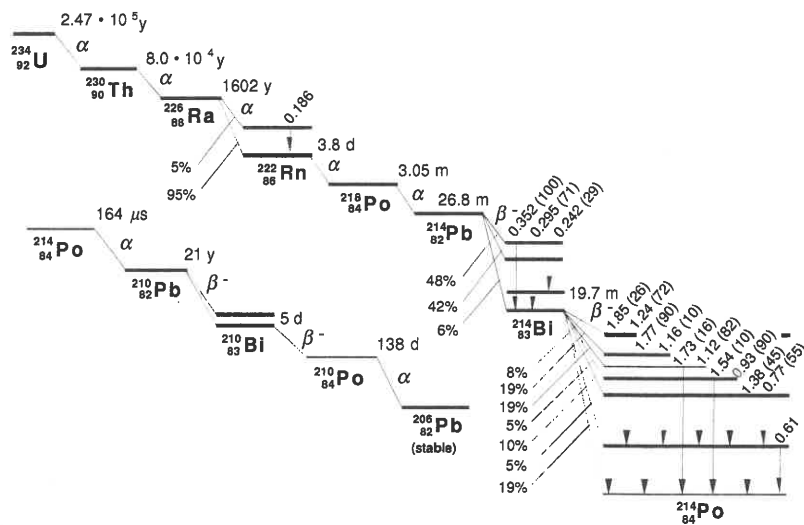


Figure 8.

4.4 Performance

Mount 2 - 4 metres of the wire between two insulated stands and connect it to the negative output of the high-voltage power supply. The positive output is grounded. The collection of the activity is preferably started before the start of the laboratory experiment. The voltage over the wire should be about 5 kV. A suitable collecting time is half an hour.

While the collection is in progress the energy calibration with the ^{152}Eu source can be started. The europium spectrum is measured for 10 minutes. For the energy calibration the photo peaks corresponding to the gamma energies 0.122 and 0.344 MeV are used (see figure 9). Do not forget to save the spectrum again after the energy calibration is made in order to save the calibration constants together with the spectrum!

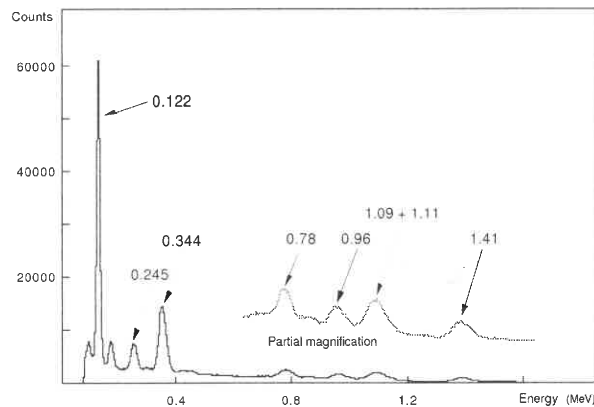


Figure 9.

Now collect a background spectrum for 10 minutes. Do not forget to remove all radioactive sources while the background spectrum is collected! The background spectrum should be saved for later use at the other computers.

On the data-collecting computer move to MSP mode by **Settings MSP mode**, which is used to measure a series of spectra with constant measuring time. The measuring time is chosen to be 600 seconds. A suitable number of spectra is 8 - 10. Before starting the acquisition, go to the collecting wire.

Turn off the high voltage. Make sure that the voltage on the wire is not dangerous (for example ground the wire), loosen the wire and wind it up on a small piece of paper or wood. Put everything in a small plastic bag or plastic foil. Quickly move the activity to the detector.

Start the measurement by answering the measuring time.

While waiting for the measurement to end, do the exercises below. When the measurement is completed, save all spectra in a common file with the command **File Save MSP**. This file is now copied to all computers.

Analyse your spectra in the following way. Read first the whole series of spectra into your computer with the command **File Open**. You can then select the different spectra in the series with the command **Settings MSP Part** or the buttons



Before analysing a series of spectra, the background should be subtracted from all spectra (for example **File Subtract**). The net spectrum obtained can now be energy calibrated by using the already calibrated spectrum, which was saved earlier (this is done with the command **Calibrate From file**). You only need to calibrate one of the subtracted spectra for the peaks of interest to be identified.

To improve the accuracy, the determination of the half life is based on two gamma transitions, 0.352 and 0.295 MeV in ^{214}Bi . Determine the areas of these peaks by summing (use the **Calibrate Centroid** routine) the part which lies above the Compton background. The procedure is repeated for each spectrum. The values obtained are written into the table below. The time of the spectrum is defined as the time interval between the start of the measurement of the first spectrum to the time in the middle of the measuring interval for each spectrum.

Spectrum no.			
No. of counts (0.285 MeV)			
No. of counts (0.352 MeV)			
Sum of the peaks			
Time of the spectrum			

Draw a diagram on millimetre paper with the number of counts on the vertical axis and the time of the spectrum on the horizontal axis.

Draw the same diagram on lin-log paper with the same choice of axes. Then describe shortly the shape of the diagrams.

.....

.....

Use the lin-log diagram to determine the half life and the decay constant. Calculations and results should be reported on a separate piece of paper, attached to this instruction.

4.5 Questions

Question 1. Try to derive equation (5) from equation (4).

$$\ln(N_0/2) = \ln N_0 - \lambda T_{1/2} \quad (4)$$

$$\lambda = (\ln 2) T_{1/2} \quad (5)$$

Question 2. What sources of error may influence the result? Try to rank these sources of error. The error in the result (an error calculation is not necessary!) can be estimated by choosing two alternative slopes of the line in the lin-log diagram and determine the corresponding half lives.

Question 3. The tabulated value of the half life of ^{214}Pb is 26.8 minutes. How long will it take for the original activity to reduce to one per mille?

Question 4. The half life of ^{137}Cs is 30 years. A source contains an activity of 37 kBq. How large is the activity after a hundred years and how many ^{137}Cs nuclei does the source then contain?

5 Measurement of Cesium Activity

(With the aid of an efficiency curve)

5.1 Purpose

To determine the activity of ^{134}Cs and ^{137}Cs in food, plants or similar samples. The laboratory exercise includes the efficiency calibration of the detector. Alternatively one can use an efficiency calibration that has been obtained earlier.

5.2 Equipment

NaI detector with accessories, calibration solution (^{152}Eu), decoction of lichen or meat or a sample which has been collected outside the school.

5.3 Theory

Because of atomic bomb tests and the accident in Chernobyl it is possible at many places to find measurable amounts of ^{137}Cs and ^{134}Cs . Figure 10 shows the gamma spectrum from a sample which contains these isotopes. The corresponding decay schemes are given in figure 11.

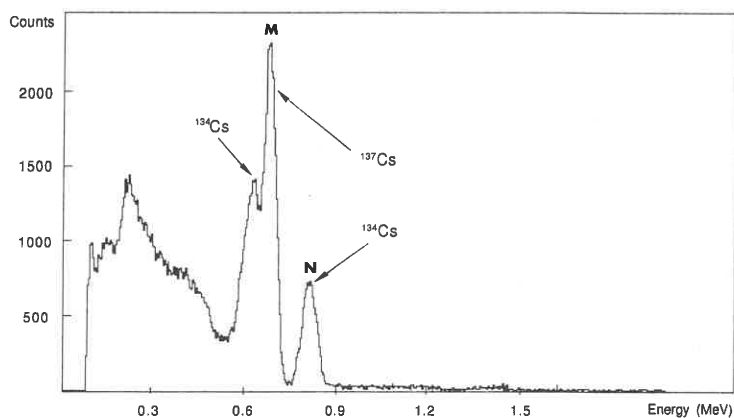


Figure 10. Gamma spectrum from sample of meat (background subtracted)

When inspecting the spectrum of figure 10 more closely one discovers that the NaI detector is not capable to resolve all energies, i. e. the corresponding photo peaks overlap. The less common (weaker) transitions are further hidden by the more common (stronger) ones. Although not all transitions are visible in the spectrum they must be considered. Study figure 11, which shows the decay schemes for ^{134}Cs and ^{137}Cs .

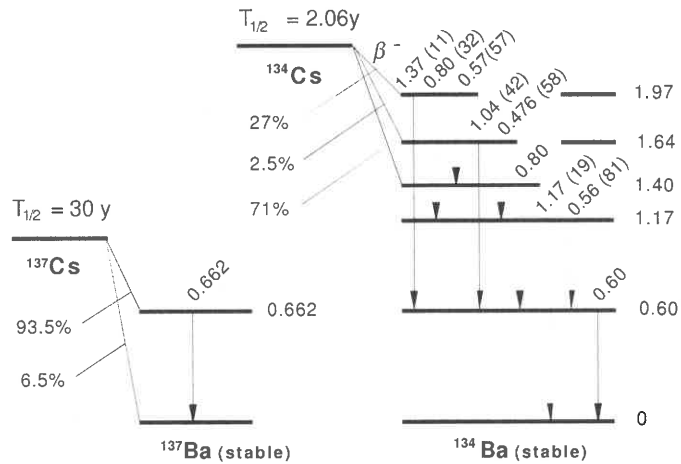


Figure 11.

The gamma energies which are of interest in the decay of ^{134}Cs and ^{137}Cs are listed in the table below together with their intensities in percent per decay.

^{134}Cs	0.56 MeV	8.4%
(see figure 10 the peak 'M')	0.57 MeV	15.9%
	0.60 MeV	97.5%
	total	121.8%

^{134}Cs	0.796 MeV	85.7%
(see figure 10 the peak 'N')	0.802 MeV	8.8%
	total	94.5%

^{137}Cs	0.66 MeV	84.1%
(see figure 10 the peak 'M')		

With the help of the decay schemes in figure 11 you may check the percentages given above. For the 0.66 MeV transition in ^{137}Ba the percentage given is lower than the value given in figure 11 since 9.4 % of the radiative transitions occur as electron radiation (so called internal conversion electrons).

From the photopeaks of the 0.796 and 0.802 MeV transitions in ^{134}Ba one can determine the activity of ^{134}Cs in the sample provided that one knows the efficiency of the detector at 0.8 MeV. The calibration is made with the help of a calibration solution of ^{152}Eu .

Since it is not possible to resolve the peak marked with an 'M' in figure 10, which corresponds to transitions in both ^{134}Cs and ^{137}Cs , one uses the peak marked 'N' to determine the contribution of ^{134}Cs in the peak 'M'. By subtracting the contribution from ^{134}Cs in the peak 'M', the intensity of the 0.66 MeV transition in the decay of ^{137}Cs is obtained.

Suppose that the number of counts in the peak marked 'N' is N , which corresponds to X decays of ^{134}Cs :

$$X = N/(k_{0,8} \cdot 0.945) \quad (1)$$

where $k_{0,8}$ is the efficiency at 0.8 MeV.

If M is equal with the number of counts in the peak marked 'M', which corresponds to the transitions 0.56 + 0.57 + 0.60 + 0.66 MeV, one can determine the number of counts (= Y) that correspond to the ^{137}Cs decays:

$$Y = M - X \cdot 1.218 \cdot k_{0,6} \quad (2)$$

The activity A of ^{137}Cs in the sample can then be calculated according to the following equation:

$$A = Y/(0.841 \cdot t \cdot k_{0,66}) \quad (3)$$

The activity B of ^{134}Cs is given by:

$$B = X/t \quad (4)$$

where t is the measuring time of the sample.

5.4 Performance

5.4.1 Energy and efficiency calibration

Collect a spectrum of ^{152}Eu . The measuring time should be about 10 min. A longer measuring time gives a higher accuracy of the efficiency calibration. Then collect a background spectrum for the same time. Subtract the background from the calibration spectrum and calibrate the energy scale using the 0.344 and 1.41 MeV peaks (see figure 12). Figure 13 shows the corresponding decay scheme.

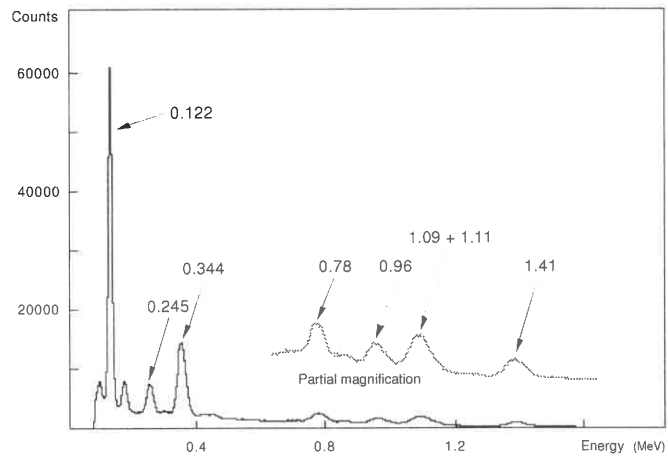


Figure 12.

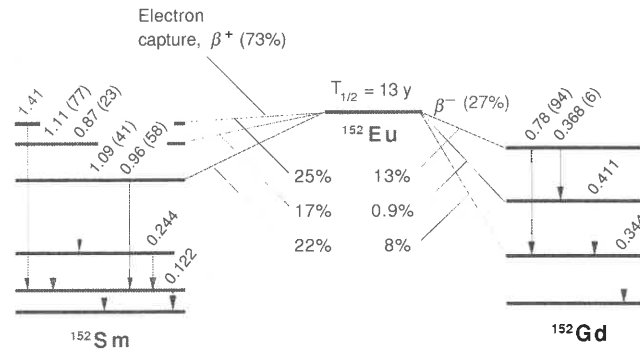


Figure 13.

For the efficiency calibration one uses the gamma transitions in the table below. The table gives the corresponding number of gamma quanta per decay of ^{152}Eu .

Calibration lines in ^{152}Eu	
Energy (MeV)	Number of gamma quanta per decay
0.122	0.307
0.245	0.079
0.344	0.272
0.78	0.133
0.96	0.145
1.41	0.214

From the numbers in the table it is possible to calculate the gamma activities for the different transitions.

Example: Suppose that the calibration solution contains an activity of ^{152}Eu of 2000 Bq. The number of gamma quanta with the energy 0.344 MeV is then given by $2000 \cdot 0.272 = 544$ per second, i.e. the gamma activity for the 0.344 MeV transition is 544 Bq.

The activity of ^{152}Eu in the solution (Bq): Measuring time (s):

The gamma activity for the 0.122 MeV transition is:

The gamma activity for the 0.245 MeV transition is:.....

The gamma activity for the 0.344 MeV transition is:.....

The gamma activity for the 0.78 MeV transition is:.....

The gamma activity for the 0.96 MeV transition is:.....

The gamma activity for the 1.41 MeV transition is:.....

Determine the areas of the different calibration peaks and write down these values in the table below. The efficiency is obtained by dividing the number of counts per second in the photo peak with the corresponding gamma activity. Complete the table and draw a graph with the efficiency as a function of gamma energy using the values from the table.

Energy (MeV)	Gamma activity (Bq)	No. of counts in the photo peak	No. of counts per sec in the photo peak	Efficiency (%)
0.122				
0.244				
0.344				
0.78				
0.96				
1.41				

Read from the diagram the efficiencies for the following energies:

Efficiency at 0.60 MeV, $k_{0.6}$ =

Efficiency at 0.66 MeV, $k_{0.66}$ =

Efficiency at 0.80 MeV, $k_{0.8}$ =

Measure the unknown sample until the peaks of interest become visible, i. e. until the statistical variation is not disturbing. The measuring time depends on the strength of the sample. For the detection of meat a suitable measuring time is at least 15 minutes.

Subtract the background spectrum and determine the areas for the peaks marked 'M' and 'N'.

The number of pulses in the peak marked 'M' (= M):

The number of pulses in the peak marked 'N' (= N):

The measuring time (= t):

Then calculate the activities of ^{134}Cs and ^{137}Cs in the sample according to the previously described theory. The calculations should be accounted for together with the result.

6 Measurement of Cesium Activity

(Simpler method)

6.1 The purpose of the experiment

By comparing the gamma intensities of ^{134}Cs and ^{137}Cs in food samples, plants etc. with a calibration solution containing ^{134}Cs and ^{137}Cs the unknown activity may be measured.

6.2 Equipment

NaI detector with accessories, calibration solution containing ^{134}Cs and ^{137}Cs and samples of various kinds containing cesium activity. The latter may be collected at places which have been contaminated by the Chernobyl accident.

6.3 Theory

Because of the accident in Chernobyl it is possible to find measurable amounts of ^{137}Cs and ^{134}Cs . Figure 14 shows a gamma spectrum from a sample which contains these isotopes. The corresponding decay schemes are given in figure 15.

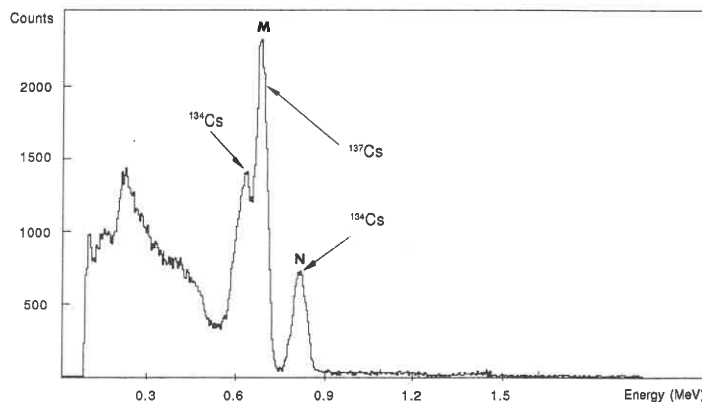


Figure 14. Gamma spectrum from sample of meat collected 1987 (background subtracted).

When inspecting the spectrum of figure 14 more closely one sees that the NaI detector is not capable to resolve all energies, i. e. that two of the photo peaks overlap.

By comparing the gamma intensity of the unknown sample, with the intensity of a sample containing the same activities to a known amount, it is simple to determine the activity in the unknown sample.

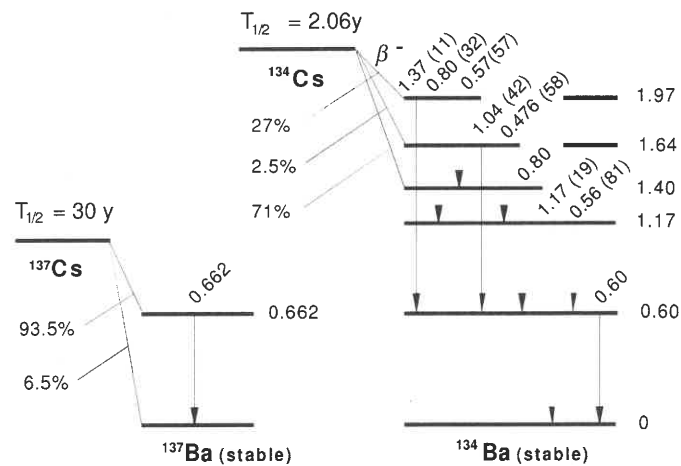


Figure 15.

6.3.1 Determination of the cesium activity

The following spectra are recorded for the activity determination:

1. Calibration spectrum (= spectrum from decoction of meat of known activity).
2. Sample spectrum (= spectrum from a sample of unknown activity).
3. Background spectrum (= spectrum from the background radiation in the room).

The analysis procedure:

1. Subtract the background spectrum from the calibration spectrum.
2. Mark the area A_1 and B_1 , respectively (see figure 16) and determine the number of counts per second in each peak.
3. Subtract the background spectrum from the sample spectrum.
4. Mark the area A_2 and B_2 , respectively (see figure 16) and determine the number of counts per second in each peak.
5. Perform the calculations according to below.

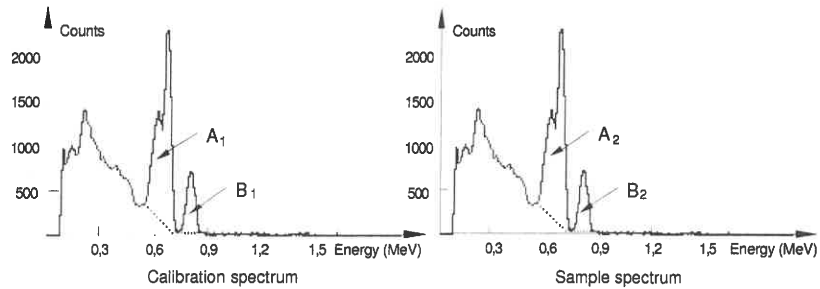


Figure 16.

Suppose that the ^{137}Cs and ^{134}Cs activities in the calibration sample are A_{cal} and B_{cal} Bq (becquerel), respectively.

The corresponding unknown activities are A and B Bq, respectively.

The ^{137}Cs activity in the calibration solution ($= A_{cal}$) =Bq

The ^{134}Cs activity in the calibration solution ($= B_{cal}$) =Bq

The activities A and B are calculated according to the following:

$$A = A_{cal} \cdot A_2/A_1 \quad (1)$$

$$B = B_{cal} \cdot B_2/B_1 \quad (2)$$

In the double peak, marked 'M' in figure 14, which corresponds to gamma quanta from both the decay of ^{137}Cs and ^{134}Cs , the relative amount of ^{134}Cs decay is always the same if the collected activity originates from the Chernobyl accident. This fact is used in the calculation of the ^{137}Cs activity when using the ratio A_2/A_1 (see equation (1)). Since A_1 and A_2 contain the same amount of gamma quanta from the ^{134}Cs decay, these contributions cancel in the division. The specific activity given in Bq/kg is obtained by dividing the determined activity with the weight of the sample.

6.4 Performance

Collect a spectrum from the calibration solution for about 10 minutes. Then collect a spectrum of the sample with the unknown activity. The measuring time should be adjusted to the strength of the activity in the sample, i.e. one should measure until the peaks of interest are clearly visible without too large statistical variations. Finally a background spectrum is collected for about 30 minutes, unless this was stored from an earlier measurement. All spectra should be saved for analysis.

The background should be subtracted from the calibration spectrum and from the spectrum of the sample. The subtraction is done by first reading the spectrum. Then give **File Subtract**. In the subtracted spectra one then determines the areas of the single and double peaks. Fill out these values in the table below.

The calibration spectrum:

The number of counts per second in the peak 'M' (= A_1):

The number of counts per second in the peak 'N' (= B_1):

	A_2 counts/s in the peak "M"	B_2 counts/s in the peak "N"	The ^{137}Cs activity (Bq)	The ^{134}Cs activity (Bq)	Weight of the sample	Specific activity ^{137}Cs (Bq/kg)	Specific activity ^{134}Cs (Bq/kg)
Sample 1:							
Sample 2:							
Sample 3:							
Sample 4:							
Sample 5:							

7 Compton Scattering

7.1 The purpose of the experiment

To investigate Compton scattering inside and outside the detector crystal.

7.2 Equipment

NaI detector with accessories, computer, scatterers of aluminium, copper and steel, lead sheets or lead bricks about 2 cm thick, ^{152}Eu calibration source and ^{137}Cs source.

7.3 Theory

A gamma quantum that interacts with the NaI crystal may deposit its energy to the electrons of the crystal in two different ways:

1. The photo effect
2. The Compton effect

In the photo-electric effect or the photo effect the whole energy of the gamma quantum is deposited in the detector. Such gamma quanta give rise to the so-called photo peak in an energy spectrum (see figure 17).

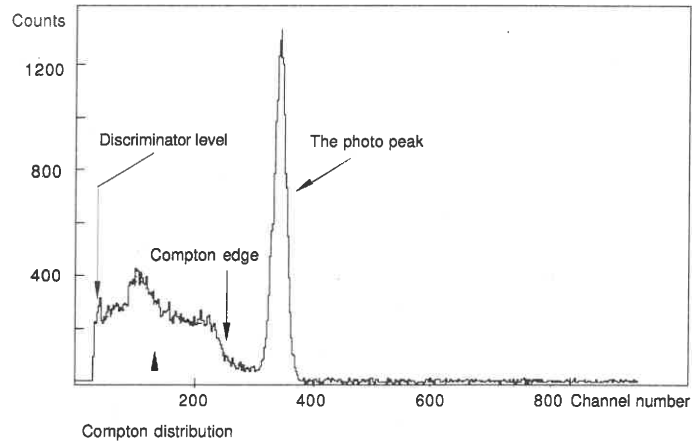


Figure 17:

Gamma quanta can also deposit only part of their energy to the electrons of the detector in a collision process which is called Compton scattering. In Compton scattering the scattered gamma quantum normally leaves the crystal. The deposited energy in the crystal depends on the scattering angle Φ (see the equation in figure 18), which for mono-energetic radiation means that the spectrum, besides the photo peak, contains a continuous distribution, the so-called Compton distribution (see figure 17).

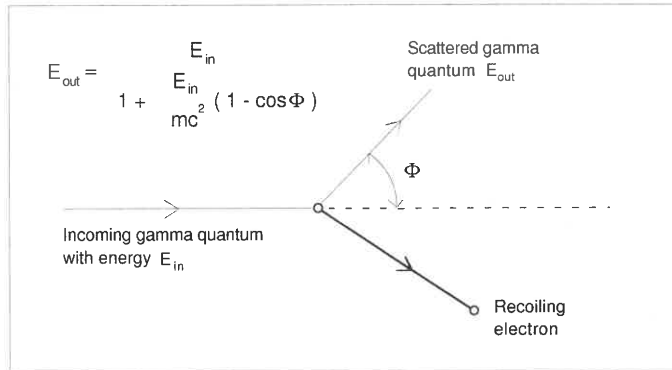


Figure 18.

By using the laws for the conservation of energy and momentum it is possible to derive an expression for the energy of the scattered gamma quantum, E_{out} . The energy difference $E_{in} - E_{out}$ denotes how much energy has been deposited to the electrons in the crystal by the scattering. It is this energy that is registered in the spectrum.

The right-hand side of the Compton distribution has an edge, the Compton edge, which corresponds to the maximum energy deposited. Determine with the help of the equation in figure 18 at what scattering angle the deposited energy has its maximum value.

Answer:

In the experiment one uses the radioactive source ^{137}Cs , where the gamma radiation is mono-energetic with the energy 0.662 MeV. Calculate the Compton edge of this energy.

Answer:

In the spectrum the position of the Compton edge is defined as the mid-point of the slope of the Compton edge, see figure 19.

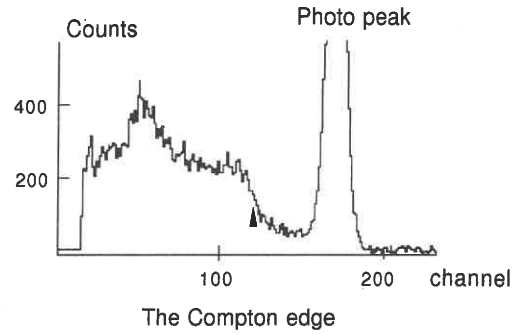


Figure 19.

7.4 Performance

7.4.1 Energy calibration

Collect a calibration spectrum from the ^{152}Eu source. The measurement time is about 6 minutes. Make a calibration with the help of the two peaks at 0.344 and 1.41 MeV. Save the calibrated spectrum.

7.4.2 Determination of the Compton edge

Put the ^{137}Cs source in front of the opening to the detector at a distance of about 5 cm to make sure that the count rate is not too high. Collect a spectrum for about 3 minutes. Use this spectrum to experimentally determine the energy of the Compton edge. The value is compared to the calculated value in the theory section.

The energy of the Compton edge was determined to be MeV

What are the sources of error in this experiment?.....

.....

7.4.3 Compton scattering with different scattering angles

In this experiment it is studied how the energy of the scattered gamma quantum varies for two different choices of the scattering angle. The experimental setup is arranged as in figure 20. To achieve a better collimation of the scattered gamma quanta, a 2 cm thick lead shield with a 2 cm wide slit is placed in front of the detector opening.

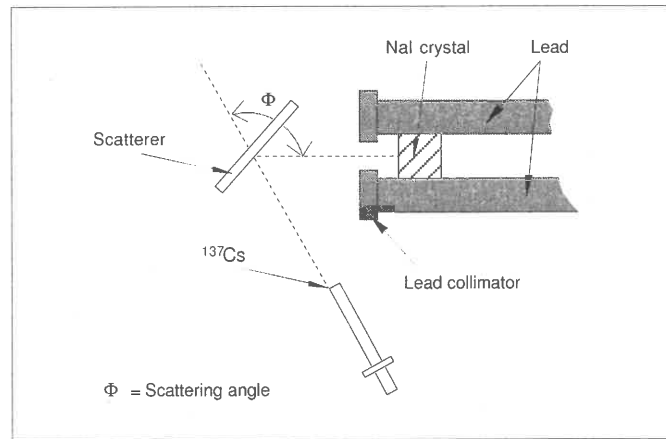


Figure 20.

By measuring the scattering angle Φ according to figure 20 one can calculate the energy of the gamma quanta scattered into the detector opening with the help of the scattering equation. This energy is compared with the energy obtained for the photo peak of the scattered radiation.

Experiment 1

The scattering angle Φ is chosen to be 90 degrees. A spectrum is collected for about 10 minutes. The spectrum is saved. The scatterer is now removed without moving the rest of the setup and a new spectrum is collected for about the same amount of time, i.e. 10 minutes.

Since the gamma radiation from ^{137}Cs also is scattered from objects surrounding the detector opening and from the detector itself and since it would be very difficult to shield against this unwanted Compton scattering, one collects a spectrum without a scatterer. By subtracting the unwanted contribution the desired effect is observed more easily.

The subtracted spectrum is energy calibrated and the energy of the photo peak is determined. This value is compared with the theoretically calculated value.

Φ : E_{in} : E_{out} :

The energy of the photo peak is.....MeV

Experiment 2

Now choose a scattering angle between 60° and 120°. Repeat the measurement procedure and the calculations of experiment 1 and report your result below.

Φ : E_{in} : E_{out} :

The energy of the photo peak is.....MeV

What are the sources of error in this experiment?.....

.....
.....

8 X-Ray Fluorescence

8.1 The purpose of the experiment

To investigate X-ray fluorescence in different materials, and to use X-ray fluorescence to identify elements in unknown materials.

8.2 Equipment

Nal detector with accessories, computer, scatterer of 3 - 4 different elements with atomic numbers between 35 and 69, lead sheets (total thickness of 2-5 mm), calibration sources containing ¹³⁷Cs and ²⁴¹Am, respectively.

8.3 Theory

8.3.1 Compton scattering

The energy of the Compton scattered radiation is given by the equation in figure 21.

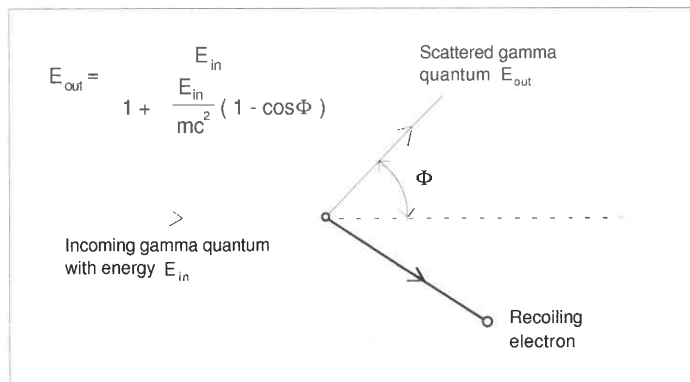


Figure 21.

Calculate with the help of the equation in figure 1 the energy of the Compton scattered radiation if the scattering angle is 90° and the incoming radiation has an energy of 0.060 MeV (= the energy of the gamma radiation from ²⁴¹Am).

$E_{in} = 0.060 \text{ MeV}$ $E_{out} = \dots\dots\dots \text{ MeV}$

8.3.2 X-ray fluorescence

If a scatterer of a heavier element is used, such as for example silver or tin, the spectra will contain additional structure besides the Compton scattered distribution. To explain the structure of such a spectrum one has to study the processes which take place in the inner electron shell of the scatterer. The primary gamma radiation emits one of the electrons of the K-shell through the photoelectric effect. Electrons from shells further out are rapidly filling the empty K-shell and at the same time energy is released by emission of characteristic X-ray radiation because of the difference between the binding energies of the electrons. This is the so called K_{α} -radiation. The process described resembles fluorescence and is therefore often called X-ray fluorescence.

Because of the choice of scattering material in this particular experiment the observed X-ray radiation consists only of K_{α} -radiation. However, also electrons from the L-shell may be emitted and thus L X-rays are emitted when the L-shell is being filled again. This radiation has much lower energy, which can be difficult to detect with the present equipment. An X-ray spectrometer is more suitable in this case.

The Englishman Moseley showed that the frequency f of the K_{α} -radiation from different elements could be summarised according to the equation:

$$f = cR(Z-1)^2 \left(\frac{1}{1^2} - \frac{1}{2^2} \right) \quad (1)$$

where c is the speed of light
 R is the Rydberg constant
 Z is the atomic number

Equation (1) resembles Bohr's equation for the Lyman series of the hydrogen atom, see equation (2). The difference is that Z has been replaced by $(Z-1)$. This is explained by the remaining electron in the K-shell, which screens the charge Ze of the nucleus by one electron charge $-e$.

$$f = cR \left(\frac{1}{m^2} - \frac{1}{n^2} \right) Z^2 \quad (2)$$

where $m = 1$ for the K-shell (K_{α} -radiation)
 $n = 2$ for the L-shell.

Equation (1) can be written

$$E = hf = \frac{3}{4} hcR(Z-1)^2 \quad (3)$$

where h is Planck's constant
 E is the energy of the $K\alpha$ -radiation.

Equation (3) implies that there is a linear relationship between the square root of the energy ($= E$) of the $K\alpha$ -radiation and the atomic number.

From equation (3) it is also evident that with the measured energy of the $K\alpha$ -radiation from an unknown element it is possible to determine its atomic number and thus identify the element. In the experiment different elements are used as scatterer. Calculate from equation (3) and their known atomic number the expected energy of the $K\alpha$ -radiation. Write down the result in the table below.

Element	Atomic number (Z)	E (MeV)

8.4 Performance

8.4.1 Adjustment of the high voltage

The ^{241}Am source is used to adjust a suitable gain of the detector to make it easier to study low-energetic gamma quanta. The gain is changed with the help of the high voltage of the photo-multiplier tube. The change is done in such a way that the photo peak of the 0.05954 MeV line lies approximately in channel number 440.

8.4.2 Energy calibration

With the proper adjustment of the high voltage, the data collection of the ^{241}Am source is started. The measurement time is about 1 minute. Without stopping the data collection the ^{241}Am source is changed to the ^{137}Cs source and the data collection continues for about 1 minute.

The characteristic X-ray radiation from the ^{137}Cs daughter ^{137}Ba gives a peak with an energy of 0.03219 MeV. The energy calibration is based on this peak and the ^{241}Am peak.

Since the program normally gives the energy value in MeV with three decimals you can mute the calibration in keV to obtain better accuracy.

Experiment 1: X-ray fluorescence

Since the gamma radiation from the ^{241}Am source has low energy, about 2 mm of lead is enough to almost completely shield the radiation. By partly shielding the opening of the detector with lead sheets it is possible to avoid direct radiation from the source, see figure 22. The experimental setup is horizontal and the ^{241}Am source is mounted perpendicular to the detector so that no direct radiation can be seen by the detector. The scatterer is mounted so that it forms a small angle with the detector opening, see figure 22.

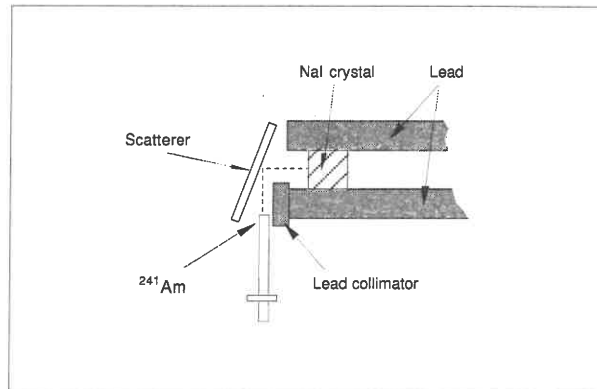


Figure 22.

One spectrum is now collected for each scatterer, and the measurement time for each spectrum is about 10 minutes. Use the previously made energy calibration to determine the energies of the peaks in the spectra. With the help of the calculated energy of the Compton scattered radiation in the theory section it is now possible to decide which of the peaks is the result of Compton scattering. The other peak originates from K_{α} -radiation. The measured values are accounted for in the table below.

Element	K_{α} -energy E (MeV)	Atomic number (Z)	E (Z-1) ²

Draw a diagram with the square root of the K_{α} -energy as a function of the atomic number.

Conclusion.....

Experiment 2: Analysis of an unknown element

Take the scatterer with an unknown element and collect a spectrum for about 10 minutes. Determine the energy of its K_{α} -radiation. Use the diagram to determine the atomic number and thus identify the unknown element.

Result: K_{α} -energy:.....

Z =

The element is:.....

Sources of error:.....

.....