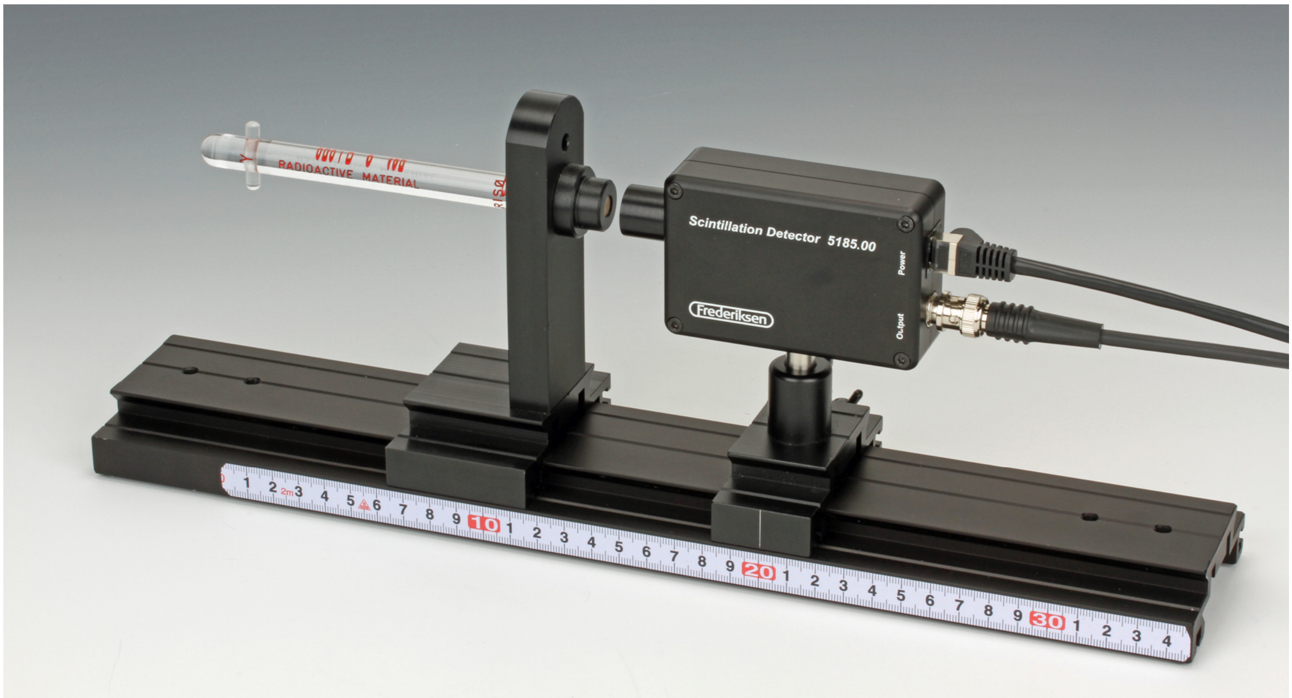
Gamma Spectroscopy, the Cs-137 source

Experiment number	138810-EN	*Topic*	Nuclear physics				
Version	2017-02-21 / HS	*Type*	Student exercise	*Suggested for*	grade 11-12+	*p.*	1/8



Objective

In this exercise, the gamma spectrum from a Cs-137 source is studied.
This is also an introduction to the gamma spectrometer and its accompanying software.

Principle

A *gamma spectrometer* consists of a *detector* (that registers the gamma quanta and responds with electric pulses, proportional to the energy) and a *multichannel analyser* (that measures the size of the electric signal and counts the number of gamma quanta registered).

The multichannel analyser contains a large array of *channels*, i.e. counters, each corresponding to a small energy interval. For each registered quantum, the analyser determines the corresponding counter and increments it by one. After sufficiently long time, the result can be plotted as a so-called *spectrum*: A graph showing the frequencies as a function of the gamma energy.

Equipment

(See Detailed List of Equipment on the last page)

Scintillation detector, multichannel analyser
Cs-137 source

Stand material

PC with the program GaSp (and related USB driver) installed in advance.

(It is important that the installation of software *is completed* before starting this exercise. If not, both time and concentration are jeopardized.)

Remember the following rule:

The connection to the detector must **not** be changed while the multichannel analyser is powered:

First connect both cables for the detector – **next,** plug in the USB cable.
When finished, unplug the USB cable **first** – the cables for the detector are unplugged **last**.

Measurement principle

The detector

A so-called *scintillation detector* is used.

It consists of two parts: A *scintillator* – a crystal of CsI – and a very sensitive light sensor.

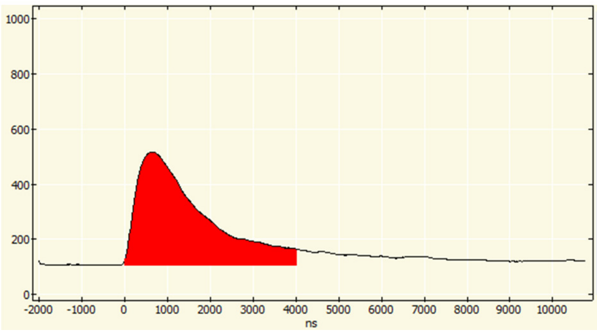
The scintillator gives off a tiny flash of light when hit by a gamma quantum. The light consists – like gamma radiation – of photons, hut each of these has far less energy than the gamma quantum. Hence, the energy of one gamma quantum is distributed among a very large number of light photons.

The light sensor gives off a small electric charge each time it is hit by one light photon. All in all, the total amount of charge is proportional to the energy of the gamma quantum.

The multichannel analyser

After the detector gives off an electric pulse, it is the job of the multichannel analyser to determine its *size*.

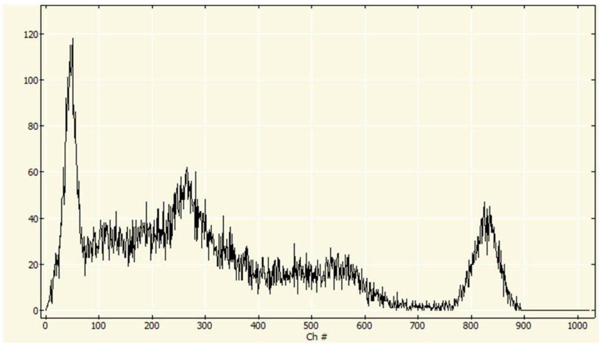
The black curve on the graph below shows a pulse as it is drawn by the program GaSp. The horizontal axis is time, measured in nanoseconds, the vertical axis is voltage, measured as a number between 0 and 1023 (without unit)



The size of the pulse is defined to be the red area between the curve and the rest level, from the start of the pulse up to an adjustable end time (here, 4000 ns is chosen).

After finding the area, it is translated into the number of a *channel*: The interval between 0 and some maximum area is divided into 1024 sub-intervals, each with an associated counter. The count in a channel is incremented every time a pulse with the correspon-ding size is received. This can be done with a speed of thousands of pulses per second.

After a while, the spectrum – the graph of the counts – could look like this:



You will notice an area around channel 50 and again around channel 830 where the graph shows a peak with noticeably higher counts than in the surrounding areas. These peaks correspond to gamma energies that occurs very frequently in the radiation from the source.

The spectrum shows a few more details that will be explained below.

The details of the spectrum

Gamma quanta interacts with matter in several ways. In the energy range that we are dealing with here, two processes are relevant:

Photoelectric effect

If the gamma quantum hits a *tightly* bound electron in one of the inner shells, all of its energy can be trans-ferred to the electron. The electron is emitted from the atom with high speed – and the gamma quantum no longer exists. As the electron carries electric charge, it will interact strongly with other electrons in the crystal. The energy is distributed among the electrons which finally settles down by emitting their excess energy as visible light.

The number of electrons that is involved in the process will vary slightly from time to time, so that a certain gamma energy will not give rise to exactly the same number of light photons every time. This is the reason that the peaks in the spectrum not just consist of a single channel but are somewhat spread out.

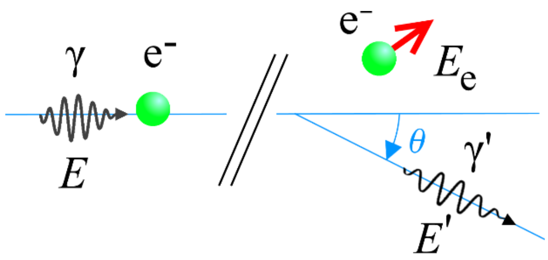
The peak near channel 830 in the spectrum above is such a *photo peak* for gamma radiation from Cs-137.

The Compton effect

If instead the gamma quantum hits a loosely bound electron in one of the outer shells of the atom, the electron can be emitted with only some of the energy of the gamma quantum.

By applying a little theory of relativity, it is possible to calculate exactly how the energy is distributed – if only you know the angle between the incoming and the scattered gamma quantum.

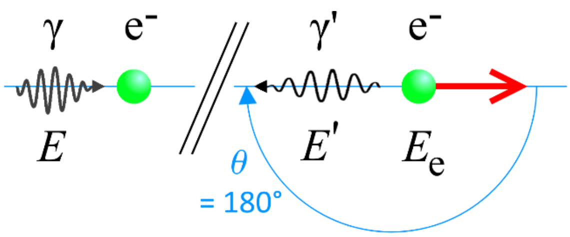
The figure below shows the situation before and after such a collision.



Conservation of energy gives that $E_e = E - E'$.

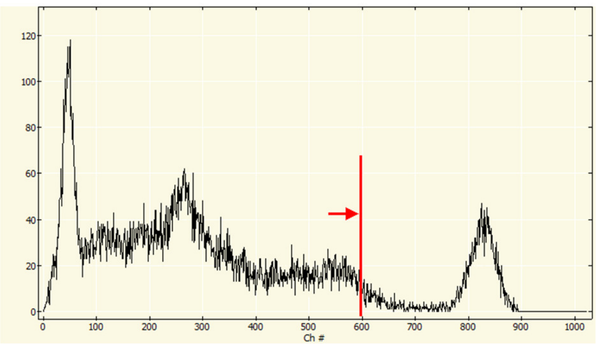
If this process happens inside the scintillator, the energy of the electron will most likely be registered – while the scattered gamma quantum may escape the detector. We will look a bit closer at the amount of energy that can be lost this way.

Intuitively it is clear that if the gamma quantum only grazes the electron with hardly any change in direction, only little energy can be transferred to the electron. Conversely, a head-on collision with a scattering angle of 180° will transfer as much energy as possible. This situation is shown below, before and after the collision:

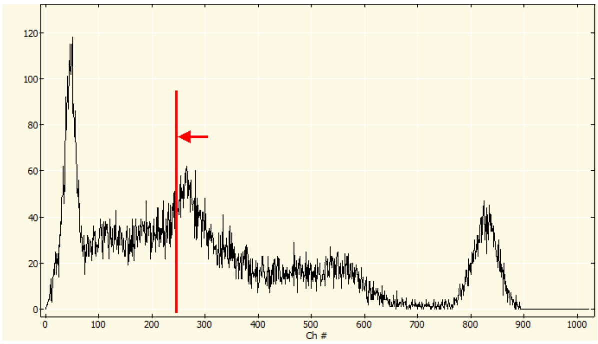


The conclusion is that if the scattered gamma quantum escapes from the scintillator crystal, then only a part of the initial energy will be registered and this part has a *maximum* value of $E - E'$, for $\theta = 180°$.

Returning to the spectrum, you can identify such a maximum energy in the shape of the edge close to channel 600:



The plateau to the left of this *Compton edge* follows a gentle arc that can be described theoretically – which we will refrain from doing! We will, however, take a look at the edge that terminates the arc to the right:



Once again we consider Compton scattering, but this time we imagine that the qamma quantum penetrates the crystal to collide outside of it. If the gamma quantum is scattered back towards the crystal and this time is registered (through the photoelectric effect), then in this case the registered energy will have a *minimum* for $\theta = 180°$. (Now, the energy of the electron escapes registration.) This fits in with the markedly lower counts below this *backscatter edge*.

Like the photo peak, these edges are not located sharply at a single channel number. As long as the detection involves an number of light photons that is not exact, positions will be "smeared". Define the position to be halfway up the slope.

X-Rays

The highest peak in the spectrum at channel 50 has not yet been discussed. This radiation is emitted from the source – but a nuclear physisist would not call it gamma radiation but *characteristic X-rays*.

It turns out that the excited daughter nucleus Ba-137* has an alternative way of decaying, namely, *internal conversion*. The excitation energy is here transferred to one of the K-shell electrons that is ejected from the atom, leaving an empty place. When one of the other electrons fills the hole in the K-shell, X-rays are emitted with an energy that is characteristic for the element involved (here: barium).

Characteristic X-rays can also be emitted by *X-ray fluorescence*, i.e. radiation that is emitted following exposure to external radiation like gamma radiation.

As mentioned previously under the photoelectric effect, a gamma quantum may rip away an electron from, for instance, the K-shell. When the hole in the K-shell is filled, X-rays are emitted like before.

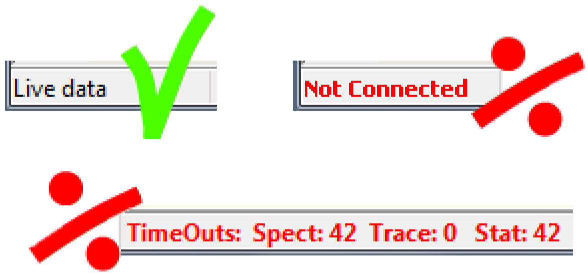
As the final part of this experiment we will demonstrate X-ray fluorescence in lead.

Setting op the program

As noted on page 1, start by connecting the detector to the multichannel analyser with both the coax cable and the 8-way cable. **Only then**, connect the USB cable between PC and multichannel analyser. Now, the program can be started.

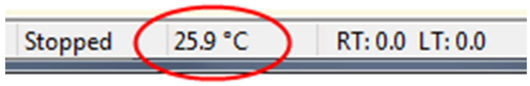
Everything OK ... ?

The status line must to the left say ”Live Data”:



If the status line says “Not connected” or perhaps “TimeOut” there is a problem with the USB connection or the drivers. Close the program down and remedy the problem before you start the program again.

The status line must also show the temperature in the detector:



If this is not the case, close the program, unplug the USB cable and check the 8-way cable to the detector.

Gain

The electric pulses need to have a certain height to be analysed correctly. On the other hand, they must not be so large that the top is clipped.

The gain is adjusted by selecting *Hardware / Detector* in the menu. This opens a window as shown below.

If the Cs-137 source is not yet in place, this is the time to place it close to the detector (see photo on p. 1).

Let the graph show *Afterglow* – this makes it easier to assess what a typical pulse look like.

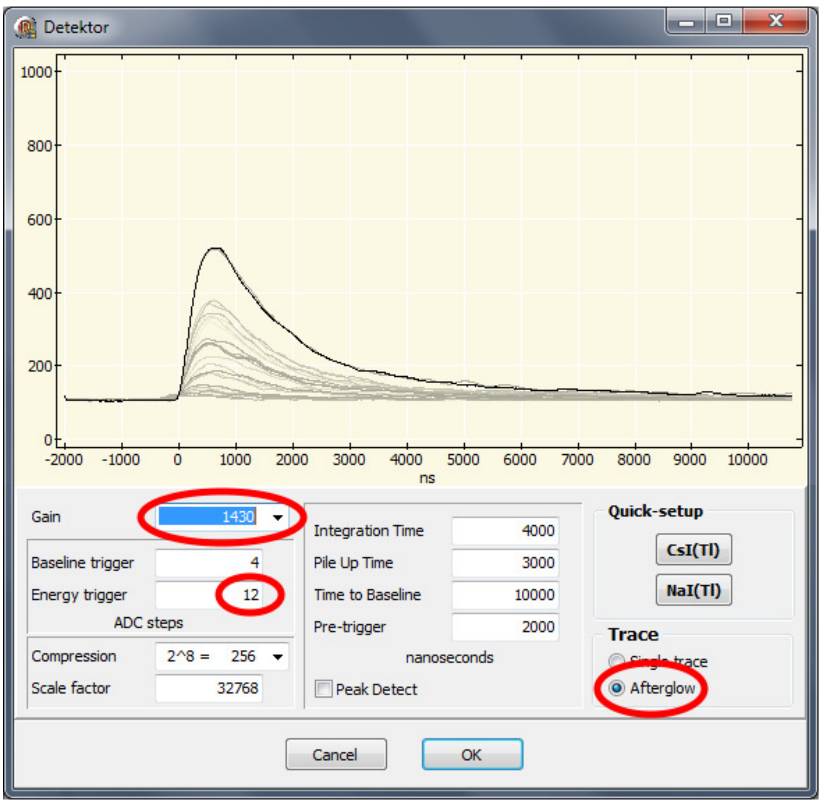
Now, select the gain that places the top of the pulse around 500 to 900 on the vertical scale. The gain steps are rather coarse.

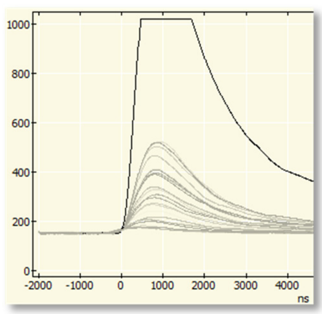
The prevalent pulses must never be clipped. But once in several seconds, a giant pulse may go far beyond limits – this is alright. This kind of signal typically originates from cosmic radiation.

Trigger level

The *Energy trigger* setting defines the lower limit for pulses to be registered. A value that is too large means that gamma rays with low energy are not registered – a value too small will allow electric noise to be included in the spectrum – more on this later.

The remaining settings can be selected as shown.





Cosmic radiation

First spectrum

We are now ready to test the setup by recording the first spectrum.

Close the dialog box with detector settings and click the *Start* button at the top left.

It takes a few minutes to obtain a good spectrum but already after 5-10 seconds, gross errors in the settings will be revealed.

If you have to tune the settings, you can click the *Zero* button afterwards to delete the spectrum and start over.

– Is there room for the complete spectrum?

The spectrum from Cs-137 is rather simple – we only need to make sure that the photo peak is included (and that there is a little free space to the right of it).

If all of the spectrum is squeezed together to one quarter of the width, you can go back and change either *Gain* or *Compression*. (The latter controls the translation between the area of the pulse and the channel number.)

– Has anything been cut off?

If *Energy trigger* is too high, the weakest pulses are discarded.

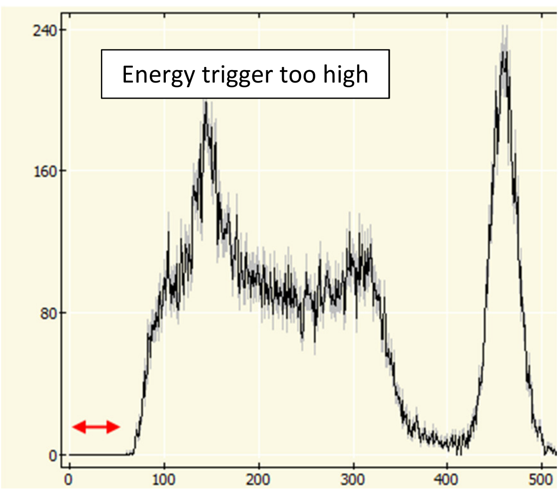
See spectrum at the bottom left where the trigger level is 5-6 times higher than it should be for these measurements.

– Are we letting in noise?

If, on the other hand, *Energy trigger* is too low, electric noise will be analysed as pulses with low energy – often with a very high frequency, giving these channels very high counts.

See the spectrum below to the right where the trigger level is about half the optimum value.

When you are satisfied with the settings, click *Stop* and then *Zero* to prepare for an actual measurement.



Setting up an experiment

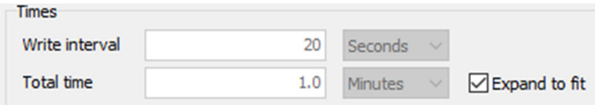
In the program, the term *free experiment* is used for the way we have worked up till now: All settings has been available and the changes has immediately had effect on the spectrum.

Now we will prepare a *spectrum experiment* – this means setting up the program to measure for a fixed time with all settings locked and to save the result automatically afterwards.

This is done by selecting *Files / Set Up Experiment*. Click the experiment type *Spectrum*.

Select for instance a total time of 5 minutes.

You must also enter the interval for writing backup copies of the spectrum.



(Backup is actually somewhat superfluous with such a short measuring time – but if you measure on a weakly radioactive sample for 12 hours, it's nice that the data has been saved in case your computer crashes after 11 hours.)

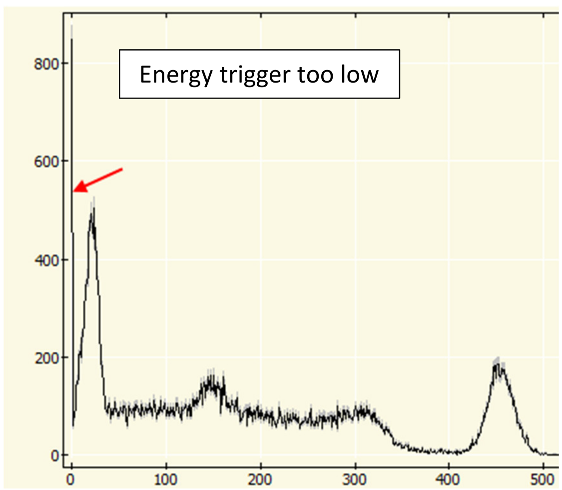
Select where the result is to be saved (and the name of the file) by clicking the … button.

Click *OK* to close and return to the main window. But remember the location and filename for later!

Start the experiment by clicking *Start*.

The elapsed time can be followed in the status line: *RT* stands for “real time”. You will also find *LT* (for “live time”) which is real time minus the *dead time* where the multichannel analyser has been busy analysing a pulse. When using typical school sources, the diffe-rence between *RT* and *LT* is only a few percent.

(After the spectrum has been collected, you must click *New experiment* when you want to reset the spectrum and free up the locked settings.)



The background spectrum

[Your instructor may ask you to omit this paragraph in order to save time.]

Some background radiation will always be present and will be registered by the detector, even when the source has been removed. To achieve the most correct spectrum, this background spectrum must be subtracted from the counts, channel by channel.

Remove the source at least a few metres from the detector when measuring background radiation.

In order to obtain a background spectrum you must measure for at least as long time as used on the “real” spectrum. It is also important to sample the two spectra with the same hardware parameters (gain etc.)

Set up a spectrum experiment as described in the previous paragraph.

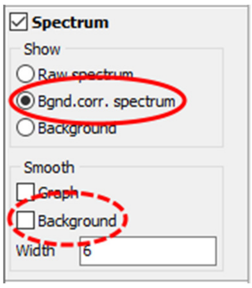
When the measurement is done, save the spectrum (one more time) as a *spectrum file*: Select menu *Files / Spectrum / Save as Spectrum file*. Make the file name contain the word “background” to make it easier to retrieve the file later.

Subtraction of the background

As soon as you have a background spectrum it can be subtracted from the current spectrum, whether this is “live” or is loaded from a file.

You already have the Cs-137 spectrum as a file – now load it back: *Files / Experiment / Read Experiment file.*

Next, use the menu *Files / Background spectrum* and click the … button to browse for the file with the background spectrum.



Open the *Spectrum* panel and chose to display the background corrected spectrum.

Unless you actively change this, the same background spectrum will be used as long as the program runs.

You may want to smooth the background spectrum lightly (but leave the foreground spectrum as it is).

The background spectrum is saved along with the foreground when saving to an Experiment file.

Energy calibration

Up till now, we have talked about channel numbers instead of energy. But if you know the energy for one or more photo peaks, the spectrum can be calibrated to make the horizontal axis have a unit like keV.

For the Cs source you can use the following:

Table values for the Cs-137 source

Gamma	662 keV
K_α (Ba-137)	32 keV

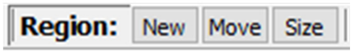
We will make a calibration based on these two points.

(We will assume that the dependency between energy and channel number is linear – which is fairly, but not exactly, correct. In case you have more sources with known data, a better, slightly nonlinear, calibration can be made.)

To determine the precise position of the peaks we will fit a so-called Gaussian curve to the data.

Specify region to fit with a Gaussian curve

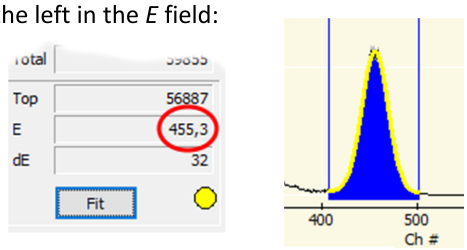
First, we must specify the region of the spectrum with the peak: Click *Region: New*, and then **drag** the mouse horizontally over the peak. The position can later be adjusted by clicking at *Region: Size* and pulling one of the two “handles” that appears on the lines.



To the left of the spectrum, a new panel appears from which you can control the fitting. With a prominent photo peak, it usually goes automatically:

Click the *Fit* button. In the next dialog box, simply click *OK*. The photo peak now should be fitted with a Gaussian curve (yellow in the figure).

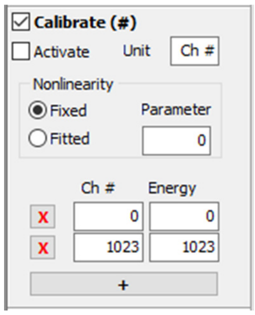
The position of the peak can now be read in the panel to the left in the *E* field:



Repeat this procedure with the X-ray peak.

Entering calibration data

Tick the box *Calibrate* to make this panel appear:



Change *Unit* from “Ch. #” to “keV”. Enter channel numbers and energies for the two peaks I the fields below.

(Avoid changing the fields for *Nonlinearity*.)

Finally tick the *Activate* field. The program now determines the translation between channels and energy. (Should an error prevent this, the tick mark will not appear. This could happen if the two channel numbers are identical.)

The horizontal graph axis will reflect the calibration and let you read off the energy directly. If you point at a detail in the spectrum with the mouse, the coordinates of the pointer can be read in the status panel.

If you fit a third peak to a Gaussian, its position will also be given as an energy.

X-Ray fluorescence from lead

[Your instructor may ask you to omit this paragraph in order to save time.]

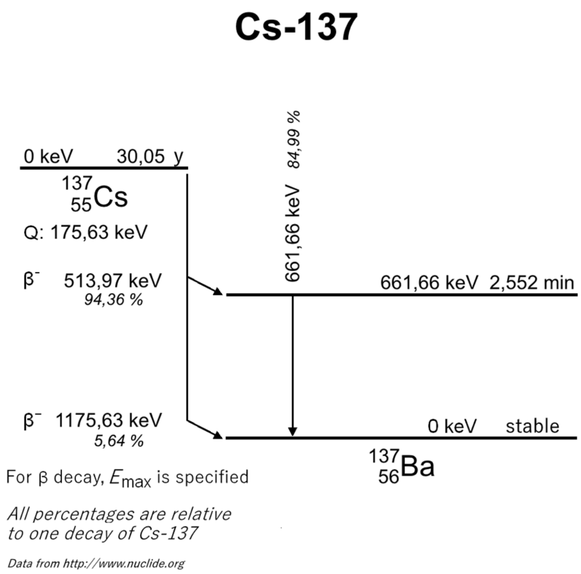
Place one or two sheets of lead (for instance arranged as a “roof” with adhesive tape) close by the source and the detector – without blocking the radiation. See photo. Placed like this, the sheets are irradiated by the source, and the X-rays emitted can be registered by the detector.

Set up a new spectrum experiment to run for 5 minutes, and start it.

The result should be an extra X-ray peak at a slightly higher energy than the one from the Cs source.

Theory

Decay scheme



The decay scheme shows the most important decay channels for Cs-137 and Ba-137*. (Internal conversion is not shown).

Compton scattering

We will not present the theory in detail but just show the formula for the energy of gamma quanta that are scattered through an angle of 180°:

$$E'(180°) = \frac{1}{\frac{1}{E} + \frac{2}{m_0 \cdot c^2}}$$

where *E* and *E’* are the energy of the gamma quantum before and after the collision, m_0 is the rest mass of the electron and *c* is the speed of light.
Be careful to use units consistently!

From *E* and *E’* the expected positions of both the Compton edge and the backscatter edge can be found.

X-Ray energy – Moseley’s law

Henry Moseley discovered in 1913 on a purely empirical base that the energy of K_α x-rays from an element follows this expression:

$$E = k_1(Z-1)^2$$

where *Z* is the atomic number of the element and k_1 is a proportionality constant. This relation has later been substantiated by quantum mechanics.

Based on the table value for the K_α x-ray from barium, try to calculate the expected energy for the radiation from lead.

Reporting

It is easy to copy the spectrum to a report by using one of the buttons at the top:

It is often a good idea to adjust the size of the window first, so it is not too large.

Inset the image in e.g. Word or a drawing program by pressing Ctrl+V – or one of the 2-3 other ways to paste something from the clipboard.

By the way, the program file itself (GaSp.exe) is easy to copy to another PC. This way you can analyse the files at home. (But you will not be able to hook up the multichannel analyser to this PC.)

The report should contain your calculations, the positions in the spectrum of Compton and backscatter edges as well as fitted energies of the peaks in the spectrum.

Discussion and evaluation

Compare the measured to the expected values.
Concerning the two edges: Estimate the experimental uncertainty of the positions of the edge.

[If you recorded a background spectrum:]

Is the background radiation the same for all energies, or are the counts unequally distributed?

Notes for the teacher

Concepts used

- Decay
- Gamma quantum
- Photoelectric effect
- Compton scattering
- Characteristic x-rays

Mathematical skills

- Evaluation of expressions
- Simple equation solving

About the equipment

The scintillation detector contains a 6 x 6 x 15 mm CsI crystal. The radiation must penetrate about 0.5 mm aluminium in the cap around the crystal.

The size of the crystal makes the sensitivity of the detector decrease for higher gamma energies.

About the software

It is crucial that the software is installed **in advance** on the PC to be used. Otherwise you risk wasting precious class time on installation.
The program gives hardly any problems but in newer Windows versions, installing the USB driver requires you to carefully follow the procedure outlined in the included Quick Start Guide (version 1.25 from Nov. 2015 - or later).

This guide is not intended as a substitute for the program manual, which should be available.

Note: It is strongly recommended that you subscribe to our mailing list for program updates.
write to: **info@frederiksen.eu**

Detailed equipment list

518000 Multichannel analyser
518500 Scintillation detector for 518000

514102 Rail for experiment bench, 40 cm
294610 Saddle with Ø 10 mm hole
514010 Absorber plate, lead, 1.2 mm (two are used)

Source holder *):
514180 Source holder, bench, simple, Risø source
or
514185 Source holder, bench, simple, disc source
or
514187 Source holder, bench, simple, cyl. source

Also required

PC with software (GaSp) ***and related USB driver***

Cs-137 source, like: 510030 Gamma source, Risø **)

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*) 514180 (for Risø sources) is shown on p. 1.
514185 is for Ø 25 mm disc sources:
514187 is for Ø 12 mm cylindrical sources (below):

Please note that the latter two types of radioactive sources are not provided by Frederiksen Scientific.

**) This gamma source is included with the 510000 Radioactive sources, Risø, complete set.

Stand material, other options

The mounting hardware above can easily be replaced by normal stand material. Positioning of source and detector is not critical in this application.

Our 514100/514120/514110 Mounting bench (including absorbers) provides an excellent alternative which is also applicable to other nuclear physics experiments.

514100 Mounting bench for Risø sources
514120 Mounting bench for disc sources
514110 Mounting bench for cylindrical sources