Advanced Physics Lab SS19

Experiment: Short half lives

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Abstract

In the short half life experiment, the half life of ^{57}Fe in the 14.4 keV state is measured with the delayed coincidence method. As the source, the Cobalt Isotope ^{57}Co is used.

Contents

1 Theory

1.1 Radioactive Decays

Radioactive Decays are spontaneous processes in which a unstable atomic nucleus transforms into another lighter one while emitting other particles. Typical forms of radioactive decay are the alpha $\beta+$ and the $\beta-$decay.
During the $\alpha-$decay a helium nucleus is emitted, reducing the atomic number by two. This form of decay is mainly found in heavy nucleus.
During the $\beta+$decay a proton transforms into a neutron and emits a positron as well as a electron-neutrino, reducing the atomic number by one.

$$p \rightarrow n + e^+ + v_e$$

On the other hand the $\beta-$decay is the reverse. It transforms a neutron into a proton and emits a electron and a electron-antineutrino. This decay increases the atomic number.

$$n \rightarrow p + e^- + \bar{v}_e$$

Another for the experiment important decay is the Electron Capture (EC) or $\epsilon-$decay. This one is similar to the $\beta+$decay since it also transforms a proton into a neutron. The difference being, that here the proton captures a electron to transform. The emitted particle is a electron-neutrino.

$$p + e^- \rightarrow n + \bar{v}_e$$

The captured electron is mostly from the K-shell while the resulting hole in the shell is filled by electrons from the L-shell. The remaining energy is either emitted through a X-ray photon or a Auger-electron. An Auger-electron is an electron that got the energy of an electron filling the vacancy left by electron in a lower state. The Auger-electron is therefore ejected.
These decays are often accompanied by a $\gamma-$decays. When a decay occurs the daughter nucleus is mostly left in an exited state. It then decays into the ground state emitting γ-rays.
Another Process similar to the γ-decay is the internal conversion (IC). Here the energy of a decay into a lower state is transmitted without radiation. That means no real photon is created to transport the energy. The energy is directly absorbed by another electron from the shell and ejected. The hole is filled similar to the one of EC by X-ray or Auger-electrons.

1.2 Interaction between Matter and $\gamma-$Photons

When $\gamma-$photons and matter interact this happens mostly in 3 different ways depending on the atomic number of the atoms in the matter, as well as the Energy E_γ of the photons.

1. Photoelectric effect:
   The photoelectric effect happens when a photon is absorbed by an electron inside the matter. The energy carried by the photon is turned into kinetic energy and frees the electron. The vacancy is filled by electrons from higher shells and the energy is emitted by an Auger-electron or X-ray.
   This effect appears mostly by $E_\gamma < 200\,\text{keV}$ and an atomic number around 50.

2. Compton scattering:
   Unlike the photoelectric effect the photons are not absorbed by the electrons in the matter. They give up a part of their energy and scatter at the electron.
   The Compton scattering happens by Energies in the range of $200\,\text{keV} < E_\gamma < 5\,\text{MeV}$ and a atomic number similar to the photoelectric effect.

3. Pair Production:
   Pair production is an effect that appears by an energy E_γ over the critical one of 1.022 MeV. When a γ-quantum gets into the electromagnetic field of a nucleus or electron it can be converted into an electron positron pair.

   $$\gamma \rightarrow e^- + e^+$$

   To create this pair the energy of 1.022 MeV is needed this is also the reason the pair production can't happen if the photon has less energy. The remaining energy is given to the nucleus. The positron annihilates with an electron shortly after it's creation into two γ-rays with each half 0.511 MeV.

1.3 Energy Spectrum

In the energy spectrum are a few areas of interest.
First of all their are the Photo-peaks. These are peaks which come into being when a photon gives its whole energy to the detector. This will happen during a photoelectric effect if the emitted x-Ray or auger electron also gets absorbed.
Another region of interest (ROI) could be the Escape-peak. Here the x-Ray emitted by an exited state dropping to back to the ground state leaves the detector without interaction. That means the Escape-peak will be shifted by the amount of energy that left the detector.
The next point is the Compton edge and spectrum. If the emitted photon only interacts with the detector only by Compton scattering, and leaves the detector only a part of the energy will be deposed. This energy will form the Compton-spectrum. For a scattering angle of 180 the maximum amount of energy will be absorbed. This energy symbols the abrupt end of this spectrum and is called the Compton-edge.
Last but not least there is the Backscatter-peak happens through photons that get scattered at material outside of the detector and find their way back in where they get absorbed. That way they lose some energy depending on the material. This is way the peak is shifted by this amount from the position of the Photo-peak.

1.4 Methodology

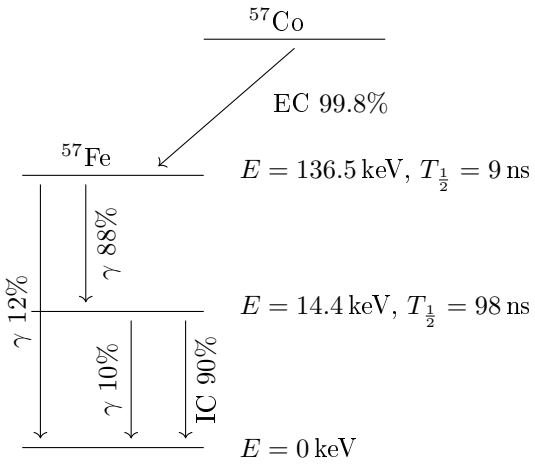

Figure 1: Decay scheme for the cobalt isotope ^{57}Co into ^{57}Fe used into the experiment to measure the half-life of the 14.4 keV state of the Iron isotope.

To measure the half-life of ^{57}Fe we use the decay of the ^{57}Co Isotope (see figure 1) ^{57}Co decays by EC into an exited state of ^{57}Fe. At this point it can either decay directly to the ground state emitting a γ-photon.
The more likely case with 88% is, that it first goes to the wanted state of 14.4 keV by emitting a $\gamma-$ray. From this state it again has two options. With a 90% probability we have an IC which we can't detect but there is also a 10% chance that a $\gamma-$decay takes place.

To measure the half-life it makes sense to use the method of delayed coincidence. For this kind of measurement we need to measure the time Δt it takes for the 14.4 keV state to decay. The γ-photons connected to this state can be used to track the creation and the decay of the measured state and with that our time Δt. This time is of interest since like the radioactive decay which is a stochastic process, it follows the equation 1.

$$N(t) = N(0)e^{\frac{t}{\tau}} = N(0) * 2^{t/T_{\frac{1}{2}}} \tag{1}$$

- $N(t)$: Number of existing nucleus at a given time.
- $N(0)$: Number of nucleus at the time zero.
- τ: Mean life time of the decaying quantity.
- $T_{\frac{1}{2}}$: Half-life of the decaying quantity.

With that the amount of measured decays at certain times Δt the half-life can be calculated. A problem that appears for the used decay is the rarity of the γ-ray with 14.4keV. This one has only a 10% chance of appearing and stopping our measurement. That would lead to a long dead time in which no new measurement can be taken. The problem is easily solved by using the rarer signal as the start of the

measurement and stopping it with the 122 keV photon. Since there are also random coincidences which will distort the measurement a background measurement has to be made. This one can be subtracted from the real measurement.

1.5 γ-Ray Detection

To detect the γ-rays two scintillators which react to the γ-photons exhibiting scintillation will be used. This again can be detected by a photomultiplier tube (PMT) and converts them into an electric pulse. As scintillators organic and inorganic ones can be used. The main difference being the decay time of the emission centers and the luminous efficiency. If the half-life is bigger than 10^{-9} s inorganic Naj(Tl)-scintillators are the choice since they have the higher luminous efficiency. For shorter times organic ones have to be used because of the shorter decay time.
For this experiment inorganic ones can still be utilized. The light from emitted can by light transmission bars to the PMTs. That way the loss will be minimized.
The PMT is used to generate an electric signal by using the photoelectric effect. The pulse is increased by using increasing the velocity of the electrons freed by the photons and using them to free even more electrons at the dynode. This process will be repeated till a useful signal is produced.

2 Experimental Setup

2.1 Energy Spectra

In the first part of the experiment the energy spectrum of ^{57}Co and ^{241}Am are measured. For this the setup in figure 2 is used. Here the signals from the scintillator gets converted into an electric pulse and the Preamplifier (PA) provides a measurable signal. In the Main Amplifier (MA) the signal gets further amplified with low-noise. After this the pulse gets to the Multichannel Amplifier were it gets registered depending on the amplitude of the signal into a channel. This way a histogram can be formed. The output of the MA is for this measurement unipolar because only the amplitude of the signal is of importance. The spectra are needed to calibrate the MCA since a connection between known energies and the channel number can be made.

Figure 2: Setup for the measurement of energy spectra with the MCA.

2.2 SCA Thresholds

In the next part of the experiment the energy windows for the Single Channel Analyser (SCA) have to be set. One have to be set to filter out 122.1 keV photons and the other one to filter the 14.4 keV ones out. For this the setup in figure 3 is used. The Linear Gate in the setup only lets through a signal only when two signals one at the input and on at the enabler arrive at the same time. That way we can precisely set the energy window at the SCA. By moving the upper and lower threshold of the window, pulses with amplitudes outside of the thresholds are stopped and with that the other signal is stopped at the gate as well. By watching the histogram created by the MCA the thresholds can be set to the correct energy levels.

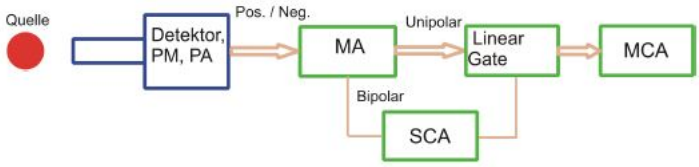

Figure 3: Setup for the calibration of the energy windows to filter out the photons with correct energies.

2.3 Delayed Coincidences

The setup in figure 4 is used to make the measurement of delayed coincidences. In this setup the two sides of the detectors are connected to the calibrated SCAs. The TAC takes a start and a stop signal and creates a signal with an amplitude proportional to the time between the input signals. Since the measurement is started with the later 14.4 keV photon the earlier photon needs to be delayed so that it can stop the measurement.

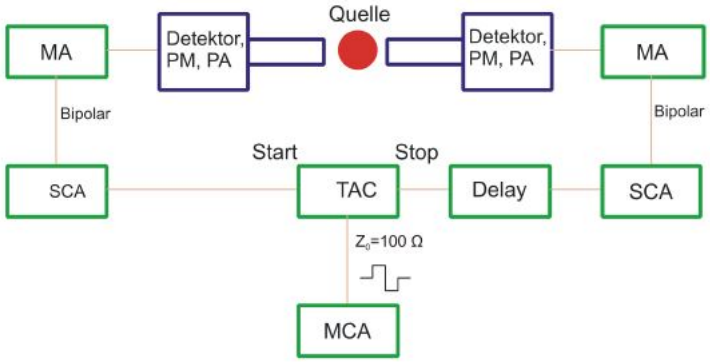

Figure 4: Setup for the measurement with the method of delayed coincidences.

2.4 TAC Calibration

Last but not least the TAC needs to be calibrated. For this the setup in figure 5 will be used. With this the constant of proportionality between the delay and the channel number of the MCA can be calculated.

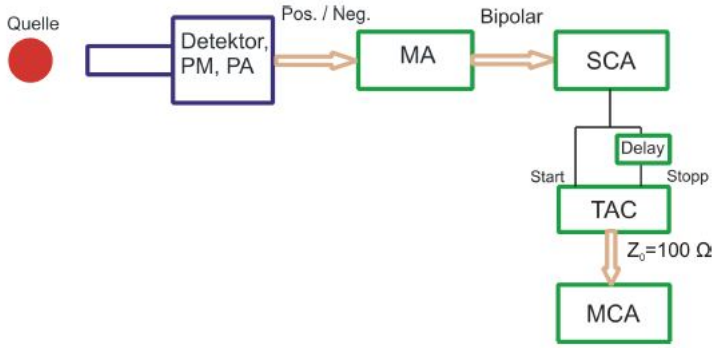

Figure 5: Setup for the calibration of the TAC.

3 Conduction of the Experiment

First of all the ^{141}Am isotope was put into the detector. Directly after the PA and the MA were connected to an oscilloscope. Here the signals of both could be compared like in figure **??**.
After this the MCA was connected like in figure 2. The MCA was also connected to the interface from which the measurement of the energy spectra can be started. With the ^{141}Am source one measurement with each scintillator was made. These can be used to make the energy calibration of the MCA.
After this measurement the ^{141}Am source was switched with the ^{57}Co source. Here four different spectra

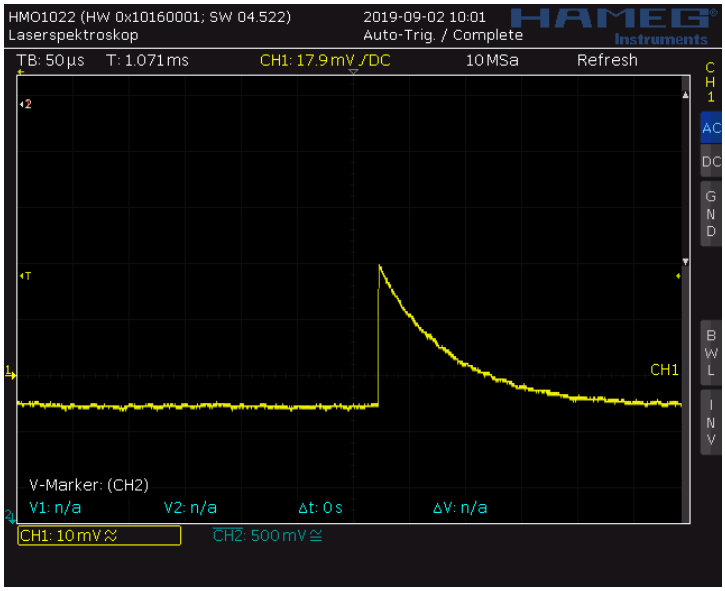

Figure 6: Signal of the PA measured with an oscilloscope.

were taken, two for both detectors with different sides of the sample. With these information the best combination of side of the sample and scintillator was chosen for the different energies. With this set the calibration of the energy windows could be started. For this the layout in figure 3 was used. First the window was opened completely so the whole spectrum, which was measured before could be seen. Than the thresholds at the SCA were slowly adjusted so that only one peak of the needed energy could be seen on the computer. After both SCAs were configured the actual measurement seen in figure 4 was set up. For the delay we choose the highest of ?? ns to get as much of the exponential curve as possible. After running a test the main measurement was started with a timer of 15 hours. Since the measured spectrum had a big part with only random coincidences this can be used instead of another measurement for the random coincidences. At last the calibration for the TAC was done by using the setup of figure 5. Here different delays were set and the corresponding channel were noted.

4 Analysis

4.1 Analysis of the Signal Shapes

In figure 6 we see the signal coming from the PA output of the detector. The signal reaches almost instantaneously its peak and than drops slowly down to the ground level. If we compare this signals with the one coming from the MA we can see that they are more Gaussian like and the beginning of the signal is a bit shifted to the left. In figure 7 the maximum of the blue signal is only a bit higher than the signal of the PA but its obvious that we have a bipolar signal. It is also notable that the ground level of the MA is higher than the one of the PA. In figure 8 this is the same but we see that the maximum amplitude of the MA signal is much higher than the one of the PA and we have a bell shaped signal. Comparing right and left slope of the MA curves with each other we notice that here the left side has a bit sharper increase than the right side of the signal.

4.2 Analysis of the Energy Spectra

4.2.1 Americium Spectra

For the Americium Isotope

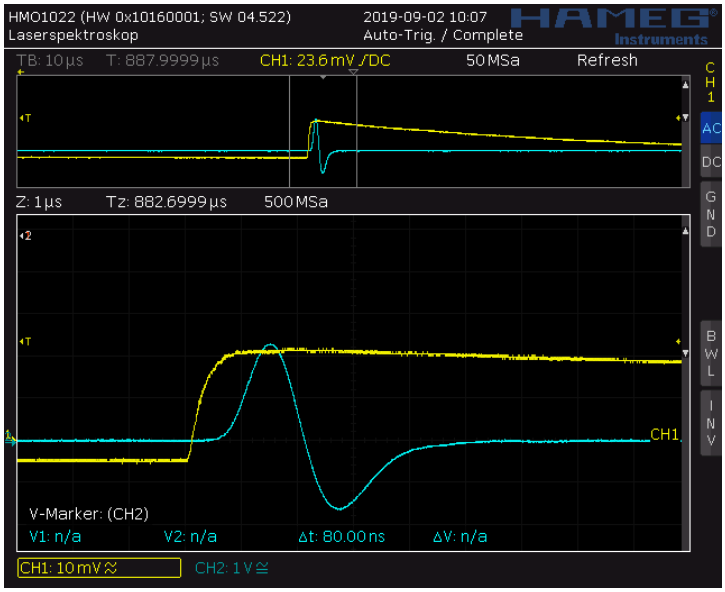

Figure 7: Bipolar signal output of the MA compared to the signal coming from the PA. Measured with an oscilloscope. In yellow the signal of the PA. In Blue the signal of the MA.

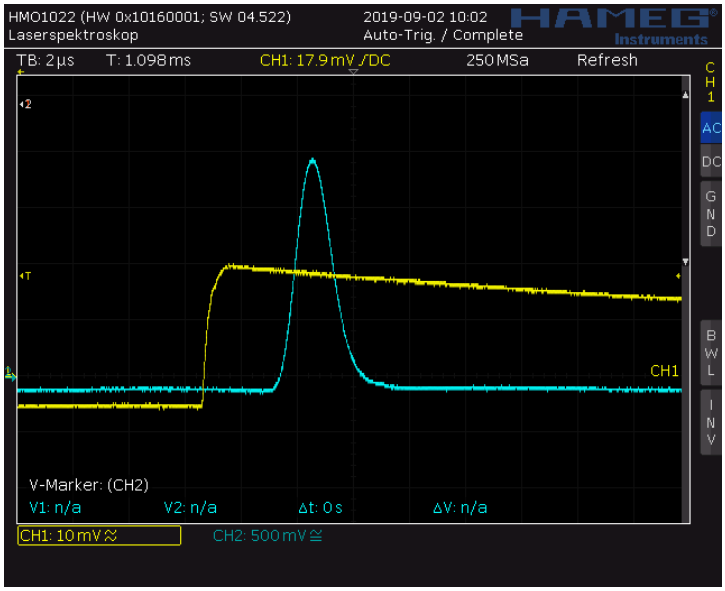

Figure 8: Unipolar signal output of the MA compared to the signal coming from the PA. Measured with an oscilloscope. In yellow the signal of the PA. In Blue the signal of the MA.

4.3 Analysis of the delayed coincidences measurement

4.3.1 Time calibration

To correctly compute the half-live of the 14.4 keV state of ^{57}Fe, the conversion of time difference to the channels in the MCA is determined. The data collected for this purpose is found in the appendix. The channel and delay pairs were plotted and a linear model of first order was fitted to the data. The plot is shown in Figure 9. The fitted linear model had the form of $n(\Delta t) = m \cdot \Delta t + c$. The fitted parameters were:

$$m = (1.2 \pm 0.007)\frac{1}{\text{ns}} \tag{2}$$

$$c = (-21.5 \pm 0.7) \tag{3}$$

The error for the time as estimated to be ± 0.5 ns, which is too small to be visible in the graphic. This parameters were used to compute the time corresponding to each channel using formula 4. x_{cal} represents the calibrated value, x_{norm} the original value.

$$x_{cal} = \frac{x_{norm} - c}{m} \tag{4}$$

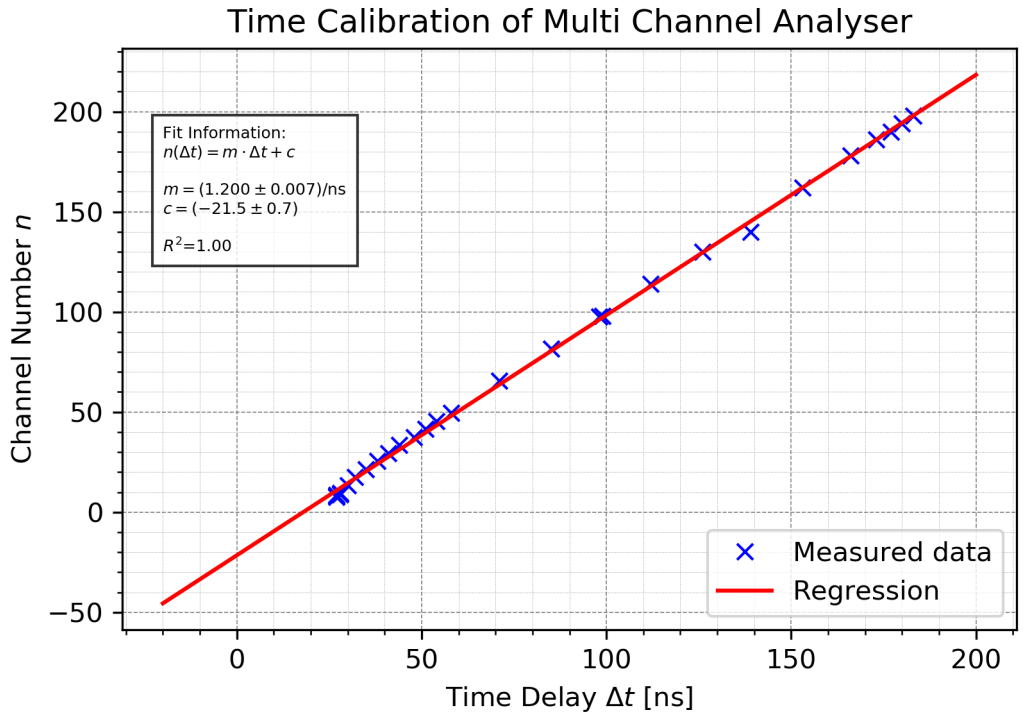

Figure 9: Plot of the datapoints of the time calibration and the linear fit of them. The errors are too small to be visible in the graphic.

References