Experimental Physics 3: Experiment I
Gamma-ray spectroscopy and neutron activation

Group B
Andreas V. Flarup 202006446
Andreas S. Niebuhr 202005667
Rasmus L. Mikkelsen 202005762
Kristoffer I. R. Pedersen 202009792
IFA Aarhus University

Abstract

In this paper we look at some properties of ^{56}Mn, it's decay product, ^{56}Fe, and the neutron source used to recharge the ^{56}Mn sample. For measuring the gamma ray energies we use a germanium semiconductor detector. We successfully found the transition energy in 5 of 7 transitions in the decay product ^{56}Fe and we estimate the branching ratios of each state. For example the first excited state is found to be $E_1 = (847.2 \pm 3.4)$keV and its branching ratio was measured to $B_1 = 0.582 \pm 0.090$. where both values are well within 1 σ of the table value.
We find the mean lifetime of ^{56}Mn to be $\tau = 3.736 \pm 0.008$h which lies just around 2σ of the table value. And the flux of the neutron source used to recharge the sample is found to be $\Phi = (2.5 \pm 0.2) \cdot 10^4 s^{-1} cm^{-2}$ using the fact that the flux is dependent on the rate of production of ^{56}Mn which is in turn equal to the activity of the decay when the sample has been charged for a long time.

1 Introduction

In this exercise, gamma-rays are used to investigate decay properties. Gamma rays are electromagnetic radiation due to excitation of the nuclei. It was first discovered in 1900 by Paul Villard and in 1903 Ernest Rutherford named it gamma rays. Further investigations revealed that the ray was electromagnetic but in contrast to x-ray the photons in gamma rays can have much higher energies [1]. The metal we are investigating in this experiment is manganese which only has the stable isotope ^{55}Mn. Mn is part of the Iron group which is produced in stars just before it explodes in a super nova and therefore it is a relatively common element in the universe [2][3]. However the ^{56}Mn isotope which we will investigate is only short lived so it will be produced from ^{56}Fe by a neutron source. This is a common way of producing short lived radioactive sources which is used in many different places. For example the techniques in medical physics, in weapons and nuclear power [4].

The energies of the gamma-rays emitted in the decay are determined. From this, the branching ratios of ^{56}Mn to ^{56}Fe as well as the partial decay probabilities of the populated states in ^{56}Fe are examined. The lifetime of ^{56}Mn will be determined. Lastly the flux of the neutron source will be investigated. ^{56}Mn is easy to work with in the lab since it has a very short mean lifetime (as

we will see) and therefore can be used in radioactive experiments like this one without having to gather large data sets. By measuring the transitions in the decay product from the ^{56}Mn sample with a germanium semiconductor detector we can accurately find all of the above values. This is done using the intrinsic properties of ^{56}Mn which allows us to look into, both how the isotope is generated and how it decays.

2 Theory

This experiment investigates the β^- decay of ^{56}Mn, where a neutron decays into a proton and emits an electron and an anti electron neutrino in the process. That is,

$$^{56}\text{Mn} \rightarrow ^{56}\text{ Fe} + \text{e}^- + \bar{\nu}_e,$$

This reaction is investigated by detecting γ rays emitted from transitions in excited states of the decay product, ^{56}Fe. That is, photons emitted from excited atoms are detected. The proton ensures charge-conservation and the anti-neutrino contributes to the lepton number with a -1 so also the lepton number is conserved.

2.1 Ge semiconductor detector

For this purpose a Ge semiconductor detector will be used. The detector consists of a semi conducting material which in this case is germanium. The germanium is in a crystal structure which lets single electrons flow across the lattice. When an incoming photon hits the material it can interact with the atoms in 3 different ways.. The first is the photoelectric effect where an atom in the matter absorbs the incoming photon γ and emits an electron e^-. From energy conservation we get

$$T_{e^-} = E_\gamma - B_{e^-}$$

Where T_{e^-} is the kinetic energy of the electron and B_{e^-} is the binding energy of the electron in a given shell. E_γ is the energy of the photon so for photoelectric absorption to occur we must have

$$E_\gamma \geq B_{e^-}$$

The second effect of interest for the experiment is Compton scattering, where a photon scatters on a weakly bound electron so the electron escapes the atom while the now outgoing photon has less energy and changes direction. Energy conservation gives that the emitted electron has energy strictly less than the original photons energy.
The third interaction is pair-production. Here a photon produces a electron-positron pair and disappears. Neglecting the kinetic energy of the atom present to ensure conservation of energy we get

$$E_\gamma = T_{e^-} + T_{e^+} + 2m_e c^2$$

where T_{e^+} is the energy of the positron, m_e is the mass of the electron, and c is the speed of light. This gives the condition $E_\gamma \geq 1$MeV. So the effect contributes at high energies. This means that how much the different effects contribute depend on the energy. Note that it is only in the photo electric effect the photon is completely absorbed such that all its energy and momenta is transferred to the electron apart from the small binding energy contribution. So the current from the electron will then almost correspond to the original photon energy. On the other hand the two other effects Compton scattering and electron positron pair production results in new photons still with high energies. Therefore the electron

only gets some of the original photon energy which corresponds to smaller current and hence a signal from a lower energy. The full picture is a little more complicated since the produced photons in the detector both can fly out of the detector since its mean travel distance is much greater than the electrons. Or it can interact with a new electron and give more energy to the detector. Since the Compton effect and electron positron effect gets more likely at higher energies one would expect fewer counts at high energies than for low energies. In practise we define the efficiency ϵ as parameter which corrects for this complicated effect. Fortunately it turns out that a good approximation is given by a power function

$$\epsilon = aE_\gamma^b,$$

with parameters a and b where E_γ is the energy of the photon. We also incorporate the geometric factor of the detectors area and distance. This is due to the inverse square law since the detector does not span the entire spherical area surrounding the source.
So when measuring counts we have the relation simply from our definition of efficiency

$$\epsilon \equiv \frac{N_{\text{measured}}}{N_{\text{expected}}}$$

where N_{measured} is the number of counts we measured.N_{expected} is the number of counts one would expect to measure giving that all the β^- decays resulted in exactly one count in the detector. So explicitly it is given by

$$N_{\text{expected}} = \mathcal{A}\Delta T\frac{\tilde{a}}{100}$$

Where $\mathcal{A}$ is the absolute activity, ΔT is the time measured and $\tilde{a}$ is the abundance at the given energy. The efficiency can be divided into the geometrical part ϵ_G and the energy dependent one ϵ_E such that

$$\epsilon = \epsilon_G\epsilon_E$$

From the inverse square law we have

$$\epsilon_G = \frac{A}{4\pi r^2}$$

Where A is the area of the detector surface perpendicular to the source and r is the distance between them. However this distinguishing is irrelevant for our experiment since we were careful to keep the distance constant with the different sources. So ϵ_G was just a constant absorbed into the a coefficient in the ϵ expression.
In order to make the germanium detector efficient one needs to cool the detector down so the background current in the material is reduced. In practise this is easily done by using liquid nitrogen which cools the detector down to 77K [5].

2.2 Neutron flux

As we shall see the lifetime of ^{56}Mn is short compared to human scale at under 3 hours. This means that we have to constantly produce the isotope in the lab. This is done by shooting neutrons on a ^{55}Mn target which can make reactions producing ^{56}Mn atoms. The neutron beam is in thermal equilibrium at room temperature, so the energy will follow a Maxwell-Boltzmann distribution. The cross sectional area for this energy distribution of neutrons is a known quantity. And the rate R of production will therefore be

$$R = \Phi\sigma\frac{m}{M}N_A,$$

where the neutron-flux Φ is the number of passing particles pr. area, and σ is the cross sectional area which represents the probability of a reaction of neutron capture to occur. The last 3 parameters represent the number of atoms in the target, where we assume that the target always is dominated by ^{55}Mn. m is the mass of the target, M is the molecular weight of ^{55}Mn and N_A is Avogadro's constant. When the target has been charged for a long time it can be assumed that the system is in equilibrium meaning that

$$R = \mathcal{A},$$

where the activity $\mathcal{A}$ is number of ^{56}Mn nuclei decaying pr. unit time. In this way, the neutron flux of a radiation source can be calculated by measuring its activity.

2.3 Branching ratios

^{56}Mn decays with 100% probability by β^- decay with the decay constant λ , which is a constant that determines the rate of decay so it is simply defined such that

$$\mathcal{A} = \lambda N$$

Where N is the number of ^{56}Mn atoms in the source. However the ^{56}Mn nuclei can in fact decay into several different excited states of ^{56}Fe. The partial decay constant for the f'th state is λ_f. The partial decay width is defined as $\Gamma_f = \hbar\lambda_f$ so the branching ratio for the state B_f is given by

$$B_f = \frac{\Gamma_f}{\sum_i \Gamma_i} = \frac{\hbar\lambda_f}{\sum_i \hbar\lambda_i} = \frac{\lambda_f}{\sum_i \lambda_i} \tag{1}$$

From where we see that branching ratio represent ratio of atoms decaying to state f pr. number of atoms decaying [6]. In practise we can only measure transitions between different states in the populated ^{56}Fe states. So we will find the branching ratios by mapping the transition energies between the states. From the transition chart [7] and known energies we can then find the number of particles N_f which decay directly to the state f by

$$N_f = N_{\text{trans from f}} - N_{\text{trans to f}}$$

Where $N_{\text{trans from f}}$ is the number of transitions from the state f and $N_{\text{trans to f}}$ is the number of transitions to the state f. Here one most of course again remember to convert the measured $N_{\text{measured}}(E)$ to $N_{\text{expected}}(E)$ through the efficiency function.

2.4 Lifetime

^{56}Mn decays with β-decay to an exited state of ^{56}Fe. All radioactive sources decay proportionally to the number of atoms. So the activity is given by

$$\mathcal{A} \equiv -\frac{dN}{dt} = \lambda N, \tag{2}$$

where N still is the number of atoms, t is the time and λ is the decay constant. Integrating the activity gives us the exponential decay law, that tells us how many atoms we have at time t:

$$\int \mathcal{A}\, dt = N(t) = N_0 e^{-\lambda \cdot t}, \tag{3}$$

where N_0 is the amount of atoms at $t = 0$. The lifetime of the substance is defined as

$$\tau = \frac{\int t \cdot N(t)\, dt}{\int N(t)\, dt} = \lambda^{-1}. \tag{4}$$

So, if we fit an exponential function to the activity, we get λ, and in turn the lifetime. [6].
Note, that it is a good idea to measure the activity for a period of time at least equal to its half life. This should not be a problem as ^{56}Mn has a half life of approximately 2.5 hours [3]. r

3 Experimental setup

The experiment was conducted by placing different radioactive samples in the middle of three germanium semi-conductor detectors as seen on figure 1. The detectors were all connected to a CAEN digitizer and the software Mc2Analyzer was used see [8]. The digitizer is needed to translate the analog signal from the detectors to a signal which can be understood by the software. The Mc2Analyzer software is used because it works well with the used digitizer.

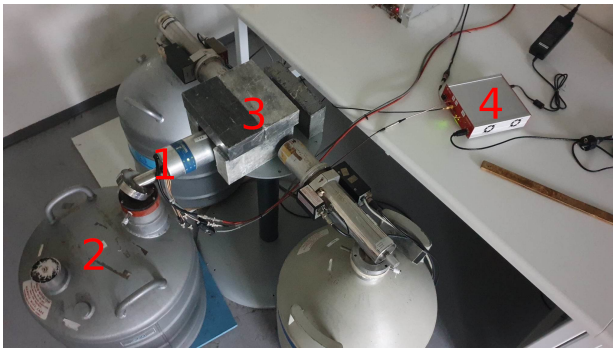

Figure 1: Three germanium detectors (1) are placed to detect activity from the sample inside the lead brick house (3). The detectors are connected to tanks of liquid nitrogen (2) to keep them cool. The detectors are also connected to a CAEN digitizer (4).

The radioactive sample is placed inside of a structure of lead blocks to reduce the amount of radioactivity in the room. This does mean that two of the three detectors is blocked by a lead block. Only the unblocked detector was therefore used and will be referred to as simply "the detector". The samples must be placed in the same location so the distance to the detector does not change. A bit of something to mark the place where the samples must be placed can be used as seen on figure 2.

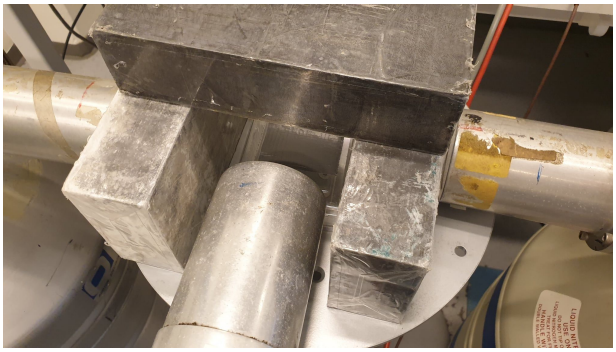

Figure 2: When changing the sample the placement must be the same so the distance to the detector is the same.

Channel to Energy Calibration

First a channel to energy calibration was made by placing ^{60}Co, ^{137}Cs, and ^{226}Ra in front of the detector. All three were used to make the calibration as good as possible. The energy of each peak of the three different samples were known and could therefore be directly related to the channel number of the corresponding measured peaks. Each of the three measurements lasted for 5 min.

Efficiency

After the energy calibration was made, more measurements were needed to determine the efficiency of the detector. ^{226}Ra sources with activity of $4.80 \pm 0.05 \mu$Ci (the uncertainty of the ^{226}Ra source was not explicitly stated, therefore the uncertainty is resorted to the last significant digit) was therefore used. The source was placed in the same place as the sources of the energy calibration and the measurement lasted for 5 min. As we will discuss later this might not have been enough time.

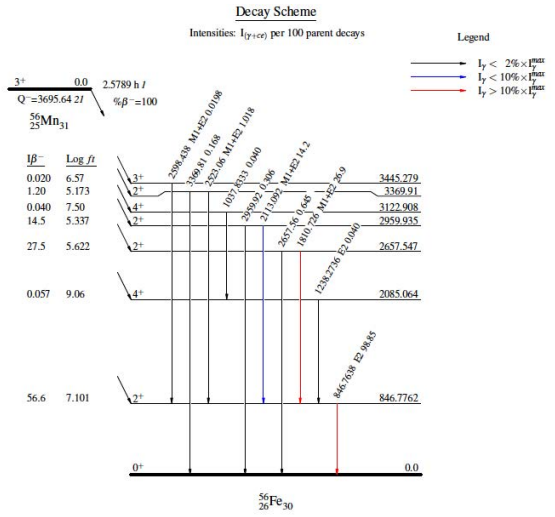

Figure 3: Branching ratios of the decay of ^{56}Mn to ^{56}Fe. The picture is from [7].

Branching Ratios & Lifetime of ^{56}Mn

The ^{56}Mn is produced by a constant neutron flux in a chamber that keeps the source radioactive. When the source is removed from the chamber and placed in the detector, one must diligently wash their hands, as radioactive dust may come thereon. The ^{56}Mn can then be measured. It is important to place it in the same location as the source used for getting the efficiency calibration due to the inverse square law. It is also important that the ^{55}Mn has been in the neutron source long enough since it will not be very radioactive otherwise. The neutron source blasts the ^{55}Mn with neutrons to make it into ^{56}Mn. Since the lifetime must be determined, a long measurement is needed. The measurement of the ^{56}Mn source therefore lasted around 16h. However for the branching ratios, a measurement of 3 hours was used. The theoretical branching ratios of ^{56}Mn can be seen on figure 3

4 Data

4.1 Channel to energy calibration

The calibration was made by finding the channel number of the peaks in the spectrum of the different sources, ^{60}Co, ^{137}Cs and ^{226}Ra since they can be related to a known energy. As seen in figure 4 Gaussian fit was then made around the peak to get a better estimate of the channel number, since the points around the peak also need to be considered. Using the actual energies of the transitions from [9] we can find the energy as a function of the channel number as seen in figure 5.

This gives the function $Ch(E) = (1.352 \pm 0.003)E - 1.3 \pm 3.1$.

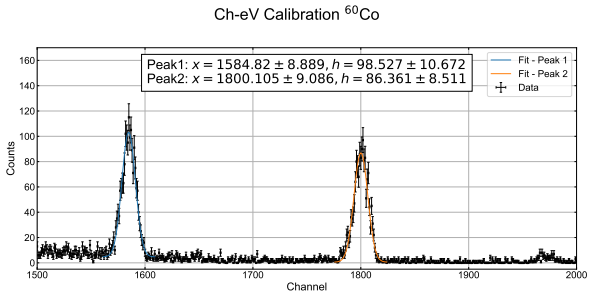

Figure 4: A Gaussian function fitted to the two transitions of ^{60}Co. The found channel (x) gives us an estimate of the channel to energy conversion factor when combined with the actual energy of the two transitions. h is the height of the Gaussian.

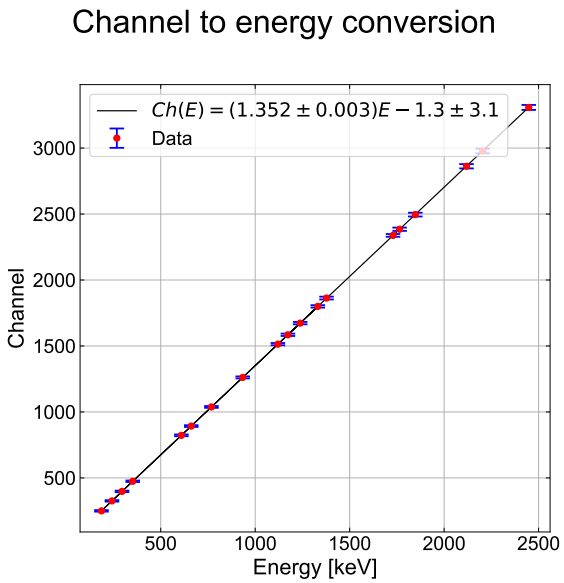

Figure 5: A linear fit to the energy - channel calibration points. The error-bars are too small to be seen.

4.2 γ-ray energy

After the Channel to energy conversion is done one can get the energy spectrum of the decay of ^{56}Mn. We then fitted Gaussian functions to the peaks on the graph 6. When the peaks are identified it is possible identify the state transition from the 8 states given in the chart of ^{56}Fe with a given peak.
From the state transition energies the energies of the excited states in ^{56}Fe can then be calculated. The results are seen in table 1.

Measured [keV]	Table [keV]	^{56}Fe state
3370.5 ± 8.6	3369.91	6
2960.3 ± 7.8	2959.94	4
2658.3 ± 7.1	2657.55	3
2085.0 ± 4.7	2085.06	2
847.2 ± 3.4	846.78	1

Table 1: The found states in ^{56}Fe. The results are all well within 1σ of the table value.

The signal for state 5 and 7 was unfortunately not measured, since the branching ratios to these states were too small. This meant that we did not have enough transitions from these states to observe a peak in the energy spectrum.

4.3 The efficiency of the detector

To get the efficiency of the detector we used two ^{226}Ra-sources of known activity. If we fit Gaussians to all the peaks of the source (as seen in figure 8), we can calculate the area of that Gaussian ($A = \sqrt{2\pi}\sigma h$) which is the measured number of decays. To get the theoretical number of decays we find Δt from our measurements, as

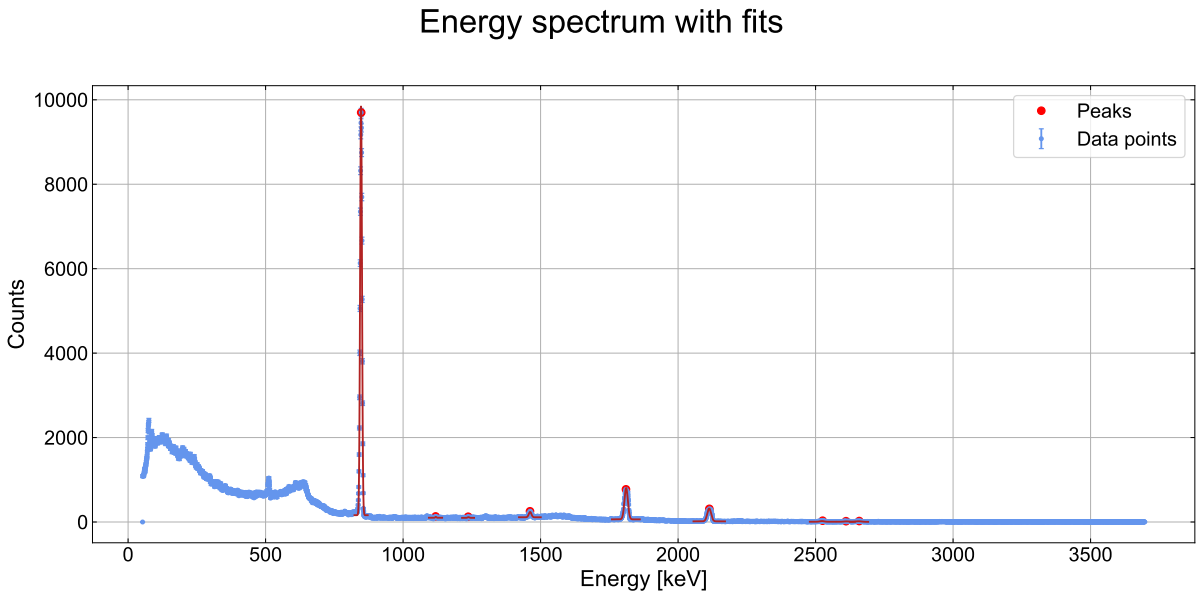

Figure 6: The energy spectrum with Gaussian fits to the relevant peaks. The peaks was first found by a peak finding algorithm from the python library scipy.signal. Afterwards they were filtered by comparison with the table values of the peaks' energy position.

a timestamp comes with every measured decay, and Δt thus is the time of the last decay minus the time of the last decay. Specially this is given in $10^8 s$ so we need to multiply with a factor of 10^{-8}. The activity is known for our specific sample to $4.80 \mu Ci = 177.6 kBq$ and we find a table of the known abundance [9]. This gives us the efficiency at the different energies of the transitions, as seen in figure 7. We then fit a power function ($f(x) = a \cdot x^b$) so that we can interpolate and extrapolate the efficiency. We get that the efficiency as a function of the energy is

$$\varepsilon(E) = (0.888 \pm 0.075 \cdot E^{-0.845 \pm 0.012}). \quad (5)$$

Note that there also is a geometrical factor in ϵ, so it is important that the calibration source and the ^{56}Mn sample is placed at the same distance from the detector.

4.4 Branching ratios to the states in ^{56}Fe

To determine the branching ratios of ^{56}Mn to ^{56}Fe it was possible to use eq. 1. The ratios have been calculated in table 2.

Many of the branching ratios have a very low chance of occurring and it is actually only the first, third and fourth branching that have a reasonable chance of occurring. The transition to the 5th and 7th state have both been measured to be 0. This is because the probability is very low meaning it requires a lot of data to see these

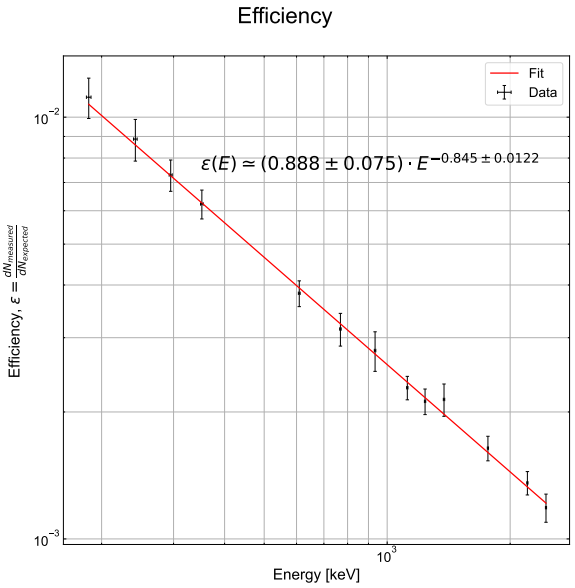

Figure 7: A plot of the efficiency as a function of the energy. As is clear from the plot the efficiency follows a power function, also given.

Measured ratio	Known ratio	State
0.582 ± 0.090	0.566	1
0.0021 ± 0.00018	0.00057	2
0.2697 ± 0.0227	0.275	3
0.1370 ± 0.0115	0.145	4
0 ± 0	0.00040	5
0.009258 ± 0.00078	0.0120	6
0 ± 0	0.00020	7

Table 2: The branching ratios of the different states from ^{56}Mn to ^{56}Fe with both the experimental ratios and the known ratios. The known ratios are from [7].

transitions.
It is also possible to calculate the partial decay probabilities for the different excited states in ^{56}Fe. In the approximation that a state n only decays to the 0th or 1st state, the probability of it decaying to one is then given by

$$P(n \to 1) = \frac{N_{n\to 1}}{N_{n\to 1} + N_{n\to 0}}$$

where $N_{n\to 1}$ is the number of transitions from the nth excited state to the first excited state and $N_{n\to 1} + N_{n\to 0}$ is the number of transitions to the ground state.
However as most of the branching ratios are very rare, the partial decay probabilities are near impossible to calculate as that requires a lot of data. We were able to calculate the decay probability from the third excited state to the first excited state and to the ground state since they were the only transitions with enough data. The probability to the first excited state was $P(3 \to 1) = 0.957 \pm 0.05$ and the probability to the ground state was therefore $P(3 \to 0) = 1 - P(3 \to 1) = 0.043 \pm 0.05$. However the table value for these decays are 0.98 and 0.023 respectively see [7].

4.5 Lifetime of ^{56}Mn

To find the lifetime of ^{56}Mn a simple exponential correlation on the form $A = A_0 e^{-\lambda t} + b$ between the activity and the time was assumed. The fit can be seen on figure 9 where the counts where collected in bins of width of 1 min.
From figure 9, the mean lifetime of ^{56}Mn can be determined from the relation $\tau = \frac{1}{\lambda}$, which for the fitted lambda value $\lambda = (0.2677 \pm 0.0006)\frac{1}{\text{s}}$, yields $\tau = 3.736 \pm 0.008$ h. The table value of ^{56}Mn is $\tau_{\text{table}} = 3.720$h, so we are just within 2σ of the table value [7].

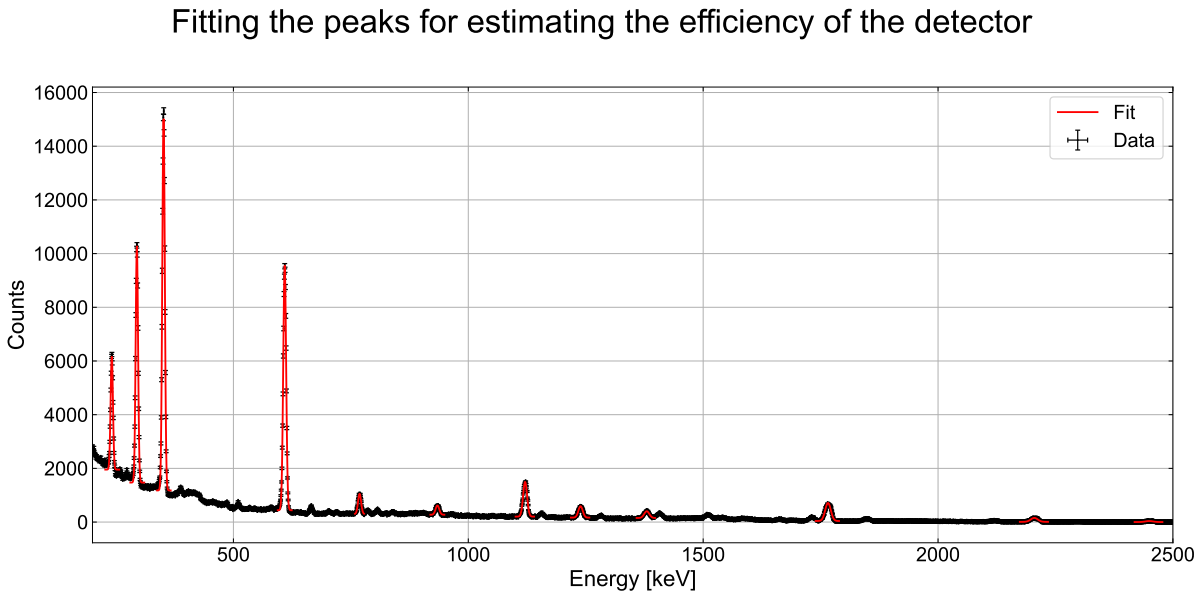

Figure 8: Fitting Gaussians to the peaks before estimating the area. The 12 peaks that we know the theoretical abundance of are fitted in red. The Gaussians are only fitted within a certain range of the theoretical value of the peak, since the background or neighbouring peaks would dominate if otherwise.

4.6 Flux of the neutron source

The abundance for the $E_\gamma = 847\text{keV}$ is known to $a = 98.85$ [9]. So it is enough to measure the counts as function of time in the interval of $\pm 2\sigma$ of the peak and then multiply with $a/100$ to get the measured number of decays. The reason why 2σ was chosen is because we then get 95% of the peaks from the $E_\gamma = 847\text{keV}$ counts, which should make it up for the background which makes close to 5% of the counts in this interval as calculated from the fit in the energy spectrum on figure 6. By using the fitted ϵ function one can find the true number of decaying particles pr. time interval. The dominating source of error is the one propagated from $\epsilon(847\text{keV})$, but due to the many precise data points in the fitting of the efficiency, we still got a reasonable small error. The result is

$$\Phi = (2.5 \pm 0.2) \cdot 10^4 \text{s}^{-1}\text{cm}^{-2} \tag{6}$$

Which is around 1σ of the table value at

$$\Phi_{\text{table}} \simeq 2.3 \cdot 10^4 \text{s}^{-1}\text{cm}^{-2}$$

From the sticker on the box containing the neutron source [10].

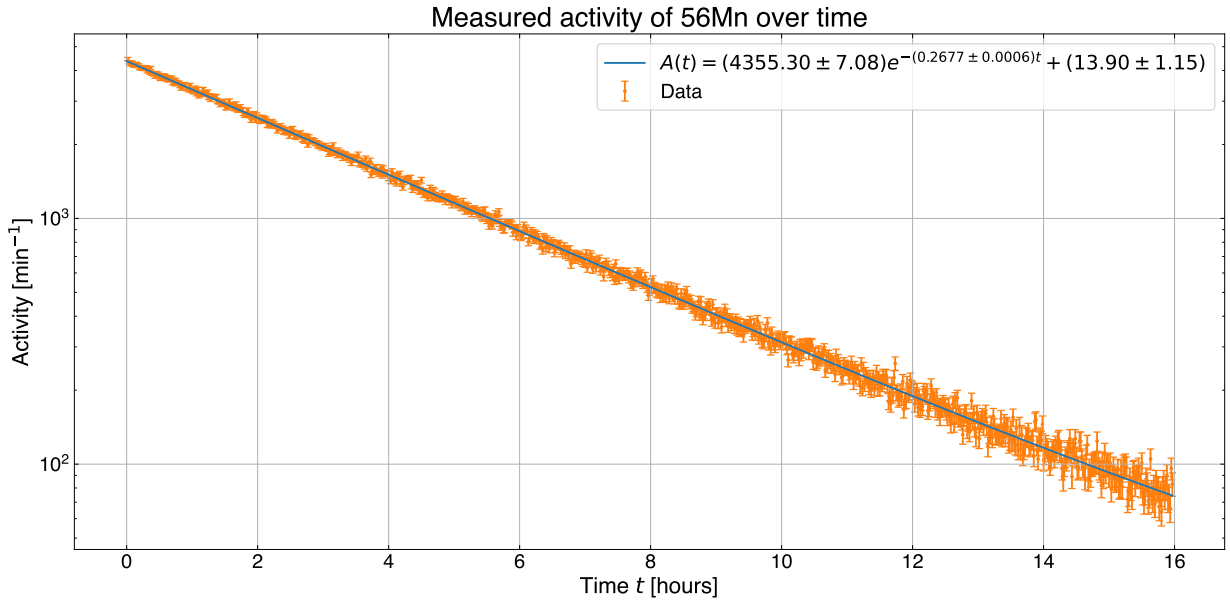

Figure 9: The activity of ^{56}Mn as a function of time. The y-axis is logarithmic so the fit becomes linear instead of exponential.

5 Discussion

5.1 γ-ray energy

The energy measurement of the excited states in ^{56}Fe is really good since they are well within the uncertainties. This is mainly due to the narrow peaks in the energy spectrum, and the good Gaussian shape of the peaks. However we did not manage to measure transitions from the 5th and 7th state. An improvement of the experiment would be to measure the decay for a longer time and also putting the source closer to the detector should give more counts. Due to the inverse square law the uncertainty in the distance between the source and the detector gets more critical when reducing it. This is another issue in the determination of the neutron flux. So one could have taken advantage of making very different constellations when measuring different things.

5.2 Partial decay probabilities in Fe

We were only able to identify the transition from the third excited stage to the first excited or to the ground state. This is because the transition probability for going to the first excited state is a lot bigger than going to the ground state for all the different excited states meaning that it requires a lot of data to be able to see all the different transitions. We did not have enough data to find the transitions in the rest of the spectrum. Should we do the experiment again a

longer measurement of ^{56}Mn is needed to be able to calculate the partial decay probabilities.

5.3 Branching ratios for ^{56}Mn

When determining the branching ratios and the partial decay probabilities in Fe, the position of the peaks is just used to identify the transition. The real challenge here is to get the number transitions with the peak energy. This both requires low uncertainty in the area of the Gaussian representing the total number of counts measured and it requires a good efficiency measurement. As seen in the results in table 2, the measurements are pretty good however there is a systematic tendency. The two lowest states are above the table value while the others are systematically under. This energy dependence in the error could indicate that the b value in the efficiency was a little off. Maybe this is because the power function does not describe the $\epsilon(E)$ data good enough to the precision this experiment requires and therefore it not is able to follow the curve enough. At first sight however this does not seem to be the case as seen in figure 7. But maybe the error-bars has been estimated a little to high such that the data was not matching that well.

5.4 Lifetime of ^{56}Mn

The measurement of the lifetime of ^{56}Mn we have found to be $\tau = 3.736 \pm 0.008$h, which is just within 2σ of the theoretical value of $\tau_{\text{table}} = 3.720$h. However the half life of ^{56}Mn does clearly follow an exponential curve as seen on figure 9. This means that there could have been a systematic error in the experiment. Maybe the detector was not at a constant temperature and correct temperature over the 16h it took to do the measurement. If we were to do this experiment again we would try to set it up in a way to better control the background radiation, as this can vary a little over time, and thereby skewer the result. This might give an even more precise value.

5.5 Flux of the neutron source

We succeeded in measuring $\Phi = (2.5 \pm 0.2) \cdot 10^4 \text{s}^{-1}\text{cm}^{-2}$. This is just around 1σ over the table value which is a good result. As discussed earlier we just took the counts in an interval of 2σ around the high peak at 847keV. So since we got the result a little too high one might suspect the ϵ value to be the systematic error again. As we saw with the Branching ratios ϵ might be a little too low at the lower energy as 847keV where the measurement was performed. If this is true, we might have calculated the total activity a little too high. As mentioned it is very important to have a good ϵ fit. Therefore it was good that we measured the most active source at 4.08μCi which gave larger count numbers. This number was still critical low at the small peaks at high energies so we should definitely prioritise a longer measurement of this source another time. Also one could consider also calculating the activity at a peak at higher energy to see if this gave a lower activity. If we had had smaller uncertainties on our branching ratios, it could also have been relevant to discuss whether we should calculate our own found abundance at $E = 847$keV. By using that value instead one might be able to get rid the potential small systematic error in our experiment.

6 Conclusion

In our working with the radioactive ^{56}Mn source we can conclude that we successfully have measured several properties of the decay process. 5 out of 7 states in ^{56}Fe has been found with energies matching the table value very well. furthermore the partial branching ratios to these states in the β^- decay was also found to a good precision. However this measurement and the measurement of partial decay probabilities in the states in ^{56}Fe depended on the efficiency which was a little harder to get, and there might have been a slightly wrong value of the b coefficient here. We also estimated the neutron flux of the thermal source to be $\Phi = (2.5 \pm 0.2) \cdot 10^4 \mathrm{s}^{-1}\mathrm{cm}^{-2}$, which is around 1σ of the table value. Lastly the lifetime was found to be $\tau = (3.736 \pm 0.008)$h. which is just within 2 σ of the table value. A general improvement to the performed experiments is to get more counts to make the precision better in the experiment.

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