IS541: Analysis review

Morten Vinther Lund, Aarhus Universitet, Institut for Fysik og Astronomi
E-mail: mvl07@phys.au.dk

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1

Energy calibration

The energy calibration has been made with three different sources: ^{60}Co, ^{152}Eu, and ^{228}Th (see a description of the sources in Table 2.1 and Table 6.1). A fit with a standard Gaussian distribution (without the normalization factor in front) were performed, in order to get the channel number of the gamma lines used. Using the uncertainty given by the fit on the centroid value and the uncertainty on the literature energy, a linear fit to the channel number versus the literature energy was made. The resulting gain and offset can be seen in Table 1.1.

During the experiment it was noticed that the amplification suddenly changed by approximately a factor of 2 (see the logbook page 22-23). To investigate this effect further, all the data files were checked to see how the channel number of the 511 keV line changed. Comparing with the logbook, to see if someone changed the gain on the amplifier, it was clear that the gain changed several times during the experiment. Both in a continuos way and, sometimes, in sudden jumps.

To remedy this it was necessary to perform several energy calibrations. For some files it was not possible to make a reliable energy calibration as the amplification were continuously drifting for some periods of time.

Table 1.1: *Parameters from the energy calibration for specific data files.*

File number	Gain (keV/channel)	Offset (keV)
1−6	No calibration performed	
7−11	0.89860(3)	−82.22(3)
12−19	1.10172(5)	−101.611(61)
20−23	Not possible to calibrate.[a]	
24−34	1.10598(5)	−102.357(62)
35−41.4[b]	1.10465(6)	−102.994(113)
41.4−43[c]	Not possible to calibrate.[d]	
44−59	1.00314(5)	−96.4839(638)
60−68	1.02224(9)	−98.096(113)

[a] Continuous shift of the 511 keV line.
[b] This calibration is done using the ^{11}Be energy spectrum.
[c] No calibration performed due to the simple ^{11}Be energy spectrum.
[d] 511 line jumps by roughly a factor of 2 during run 41 file 4. After run 43 the gain is manually changed on the amps.

2

Efficiency calibration

In order to measure the number of ^{11}Be atoms collected on the copper plate, we were using an HPGe-detector to look for gammas from the decay of ^{11}Be. The energy spectrum for ^{11}Be can be seen on Figure 2.1.

To extract the number of ^{11}Be atoms collected on the plate from the HPGe energy spectrum, we need to understand the detector efficiency as a function of energy. The efficiency of the detector depends on the setup around the detector, as this is responsible for scattering and attenuation, which both depends on the energy of the gammas. Another dependency is the solid angle coverage of the detector. Therefore, it is important to have the sources in the exact position, as where the catcher plate is placed, in order to have a reliable measure of the efficiency. If the sources are placed differently one need to correct for this, which will introduce systematic errors.

To understand the efficiency of the detector, the three calibration sources were used (information about the sources can be seen in Table 2.1 and Table 6.1). They were either positioned at the catcher position or attached to the lead piece just in front of the detector (with the lead between detector and source). Several data files were taken with various measurement times.

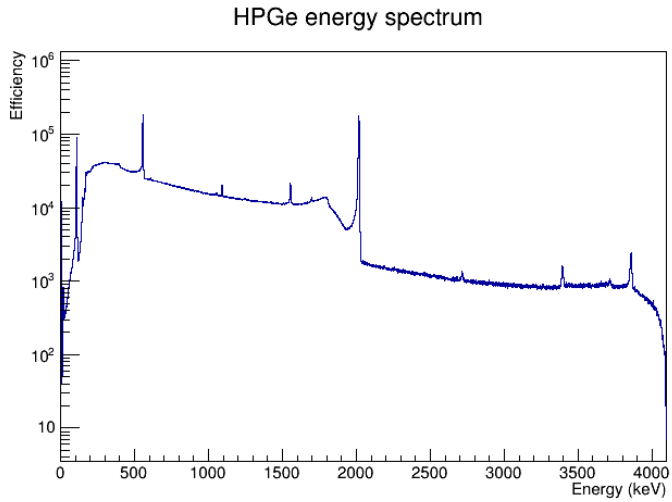

Figure 2.1: *Energy spectrum of ^{11}Be from part of the data.*

To do the efficiency calibration, knowledge of several things are needed. Here follows a small description of the calibration procedure.

For the calculation of the efficiency we first of all need to know the number of decays from each source during the measurement time. This number is given theoretically by

$$\#\text{decays} = N(t=0) - N(t) = N_0(1 - e^{-\lambda t}) \tag{2.1}$$

To know the number of nuclei, N_0, at the beginning of each data file, it is necessary to know the activity of the sources at the day of the experiment, which is given by the standard exponential decay curve and the reference activity, A_0, given in Table 6.1. An uncertainty on the activity of 2% is used according to the data sheets of the sources.

For the measurement time, the *clock* variable in the daq is used, which counts the time in milliseconds. A statistical uncertainty of 5 seconds is conservatively assumed. It is chosen to account for the scenario where the data collection is started before the source is placed correctly or stopped after the source is removed.

It is also necessary to know the number of decays as seen by the detector. For this a fit to the best resolved gamma lines were done using the fitting function given as

$$f(E) = p_0 + p_1 \cdot E + \int_{E_-}^{E_+} p_2 \cdot \frac{1}{\sqrt{2\pi} \cdot p_4} e^{-\left(\frac{E'-p_3}{p_4}\right)^2/2} \cdot dE' \tag{2.2}$$

$$= p_0 + p_1 \cdot E + p_2 \int_{E_-}^{E_+} \cdot \frac{1}{\sqrt{2\pi} \cdot p_4} e^{-\left(\frac{E'-p_3}{p_4}\right)^2/2} \cdot dE' \tag{2.3}$$

$$= p_0 + p_1 \cdot E + p_2 \left[\text{Errfcn}\left(\frac{\left(E + \frac{p_5}{2}\right) - p_3}{p_4} \right) - \text{Errfcn}\left(\frac{\left(E - \frac{p_5}{2}\right) - p_3}{p_4} \right) \right] \tag{2.4}$$

where

$$\text{Errfcn}(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2} dt, \quad x = \frac{E - \mu}{\sigma} \tag{2.5}$$

In the above the background have been estimated as a linear function with parameters p_0 and p_1. The meaning of the other parameters are that p_2 is the area of the peak, p_3 is the centroid of the Gaussian, p_4 is the standard deviation of the Gaussian, and p_5 is the bin width of the histogram.

This is a simplified parameterization of the line shape, however, as long as the same function is used for the efficiency calibration and for the actual estimation of the amount collected, the result should be consistent. This produce might though introduce a systematic error in the result but it should not be large.

It should be noted that the width of the fitting interval is scaled with energy in a simple manner for all gamma lines (the interval is set to $\pm$ 1.5% of the centroid value), in order to take care of the natural energy dependence of the gamma width with increasing energy.

Finally it is also necessary to know the total intensity of the gamma lines used for the calibration. These are given in Table 2.1 in per cent. The uncertainty

on the gamma intensity is not used in the efficiency calculation as the activity and measurement time uncertainties dominate by far.

For the overall statistical uncertainty on the efficiency a simple estimate by the law of error propagation, without taking correlation terms into account, is used. The individual uncertainties that add up are coming from the activity, the measurement time, and the error on the fitting parameter p_2 (i.e. the peak area).

Table 2.1: *Energies and gamma intensities used for the three sources in the efficiency calibration.*

Source	Energy (keV)	Intensity (%)
^{60}Co	1173.228	99.85
	1332.492	99.9826
^{152}Eu	778.904	12.970
	964.079	14.605
	1085.869	10.207
	1112.074	13.644
	1408.006	20.850
^{228}Th	583.187	30.5
	727.330	6.67
	860.557	4.49
	1620.50	1.47
	2614.511	35.852

In conclusion the efficiency is given by the following expression

$$\text{eff}(E_i) = \frac{\text{(number of counts in detector)}}{\text{(total number of decays)}} \left(\frac{\text{B.R.}_i}{100}\right)^{-1} \tag{2.6}$$

where the number of counts in the detector is given by the parameter p_2 in the fitting function in equation (2.4), the total number of decays is given by equation (2.1), and B.R.$_i$ is the gamma intensity in per cent given in Table 2.1. Using (2.6) the efficiency is given as a dimensionless fraction.

Following the above described steps results in Figure 2.2 for the efficiency fraction. Those located at a high efficiency are from sources mounted at the lead piece in front of the HPGe-detector. The others are with the source mounted in the catcher position. The data clearly looks consistent.

The next step is to correct the efficiencies measured with the source at the lead piece, so that it corresponds to the source being in the catcher plate position. To accomplish this it is necessary to make two corrections - one for the attenuation in the iron flange and copper plate, and another for the changing solid angle as seen by the detector.

The correction for the attenuation can be done in a simple manner described by the following formula

$$\frac{I}{I_0} = e^{-\mu(E)\cdot t} \tag{2.7}$$

where t is the thickness in units of g/cm^2 and μ is the mass attenuation coefficient in units of cm^2/g. The gammas need to pass through a thickness of

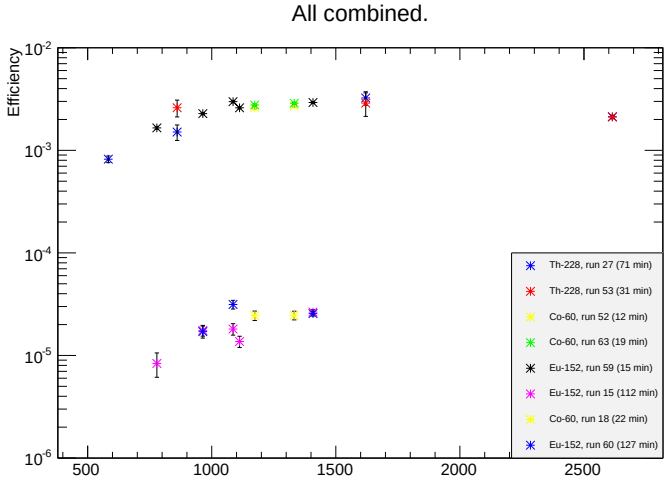

Figure 2.2: *Efficiency fraction versus energy in keV. The figure includes all efficiency data before any corrections are made. At the top are those with the source attached to the lead piece in front of the HPGe-detector. At the bottom are those with the source in the catcher position.*

1.788g/cm^2 of Cu and a thickness of 9.42g/cm^2 of Fe. The mass attenuation coefficient has an energy dependency which also gives an energy dependency to I/I_0. The mass attenuation coefficient has been found in a reference table at `http://www.nist.gov/pml/data/xraycoef/` for certain values of energy. To get the mass attenuation coefficient at the actual energy of the gammas used, a linear interpolation between two neighboring data points was done.

To get the overall attenuation factor the attenuation in the Cu and in the Fe are calculated separately. Afterwards these are multiplied to get the overall attenuation factor, which are used to get the number of gammas seen by the detector if the source had been in the catcher position. The uncertainty on the attenuation factor is not used in the calculation. It is enough that the data are consistent after the corrections, because several data points, all taken with the source in the catcher position, are giving a good description of the behavior here.

After the attenuation correction is done, it is necessary to correct for the different solid angles. For this it is used that measurements with a ^{60}Co source, both in the catcher position and at the lead piece, have been performed. Actually there are two measurements from the lead piece in front of the HPGe detector, and two measurements from the catcher position. But apparently the two measurements taken in the catcher position are not consistent with each other, and the one which fits the rest of the data the best are chosen.

Taking the ratio of the attenuation corrected efficiencies measured with the source at the lead piece, with the efficiencies measured in the catcher position, gives a correction factor which can be used. The data from run 18 and run 63 are used for this (see Figure 2.2). The correction factor has an uncertainty coming from the uncertainty on the efficiencies, which is calculated without accounting for correlation terms.

As there are two gammas from ^{60}Co, there are two correction factors. To get a better estimate of the correction factor in the energy region of interest, i.e. around 2.1 MeV[1], a weighted average of the two correction factors is made. The weights used are given by $w_i = 1/\sigma_i^2$.

The reason for this approach to the solid angle correction are twofold. First of all the solid angle seen by the detector depends on the energy of the gamma, due to different path lengths inside the detector. Secondly, it is necessary to know the size of the crystal and the exact position inside the detector of the crystal to know the solid angle. Neither of these informations are known. So several unknowns exist, which will introduce an extra uncertainty for the efficiency.

As the ^{60}Co gamma lines are quite intense and therefore are reliable for efficiency calibration, they are a good way to correct for the unknowns mentioned above. The energy of the gammas are 1.17MeV and 1.33MeV which are relatively close to the 2.124MeV gamma from ^{11}Be. As the correction should vary with energy, this approach will introduce a systematic error, and the size of the error will change with energy. The result is the introduction of a larger spread in the efficiency data after doing this correction.

It is important to note that the data taken in the catcher position does not suffer from the same systematic uncertainties as the data which are corrected for solid angle and attenuation. Therefore the most reliable data are the ones taken in the catcher position, which are run 15 (^{152}Eu), run 18 (^{60}Co), and run 60 (^{152}Eu). See also Figure 2.2. Furthermore the signal-to-noise ratio are higher for the ^{60}Co lines due to the high gamma intensities.

Another point, which is important, is that the attenuation of gammas mainly happens at low energy, and therefore the high energy ^{228}Th gammas and the ^{60}Co gammas are not affected much by this effect. They should therefore be reliable to calculate the absolute efficiency, which is exactly what is done, see Figure 2.3.

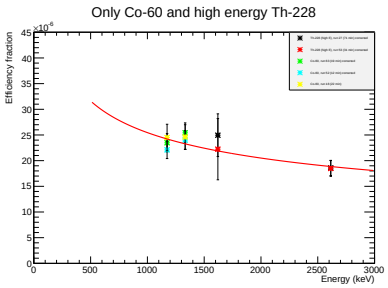

Figure 2.3: *Absolute efficiency fraction versus energy in keV. The fit to the actual absolute efficiency fraction data is shown.*

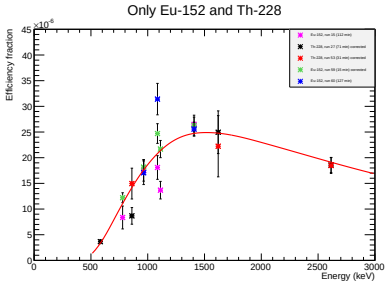

Figure 2.4: *Absolute efficiency fraction versus energy in keV. The fit to determine the systematic uncertainty for the absolute efficiency fraction data is shown.*

As the cross section for various photon processes are described by power laws, it is possible to use a fitting function to get the absolute efficiency given

[1]The strongest gamma line from the decay of ^{11}Be have an energy of 2.124MeV.

by

$$\varepsilon(E) = e^{p_0 + p_1 \cdot \ln(E)} \tag{2.8}$$

A fit with this function to the efficiency from the ^{60}Co and high-energy ^{228}Th gamma lines can be seen on Figure 2.3. The following fitting parameters from Minuit2 with Minos error estimation have been obtained:

$$p_0 = -8.42 \pm 0.64$$
$$p_1 = -0.31 \pm 0.09$$

The reason for not using more parameters are the low number of data points combined with the rather small energy dependence, which the data exhibit.

To get a measure of the systematic uncertainties a second fit was performed. The systematic uncertainties are mainly attributed to differences in the attenuation of gammas in the lead pieces. But other contributions are present as well. As the attenuation mainly happens for low energy gammas, it will be enough to look at gammas from ^{152}Eu and ^{228}Th. The high energy ^{228}Th gammas are included in order to get the correct functional behavior at large energies. To describe the physics of the attenuation correctly an absorption factor is introduced, similar to (2.7), which results in the following expression

$$\varepsilon(E) = e^{-\left(\frac{\mu(E)}{\rho}\right) \cdot \rho \cdot p_2} \times e^{p_0 + p_1 \cdot \ln(E)} \tag{2.9}$$

Here μ is the mass attenuation coefficient for gammas in lead with units of cm^2/g and ρ is the density of lead. The data was found at `http://www.nist.gov/pml/data/xraycoef/`.

A fit with this function can be seen at Figure 2.4 and the following fitting parameters from Minuit2 with Minos error estimation are obtained:

$$p_0 = -0.27 \pm 1.14$$
$$p_1 = -1.13 \pm 0.14$$
$$p_2 = 3.50 \pm 0.25$$

The final efficiency obtained gives the following result

$$\varepsilon(E = 2124\mathrm{keV}) = 2.01(8)_{\mathrm{stat}}(21)_{\mathrm{sys}} \cdot 10^{-5} \tag{2.10}$$
$$\varepsilon(E = 2895\mathrm{keV}) = 1.83(12)_{\mathrm{stat}}(8)_{\mathrm{sys}} \cdot 10^{-5} \tag{2.11}$$

The statistical uncertainty are coming from the fitting parameters in equation (2.8), and the systematic uncertainties are given by the difference between the two fits.

An efficiency calibration was also made during the experiment. The calculation of the individual efficiency data points are consistent for the two methods, however, for the final efficiency result above they does not agree. The calibration outlined here results in an efficiency, which is a factor of two higher than the one performed at the experiment. This is mainly due to the different methods of fitting the efficiency data points.

3

Number of ^{11}Be atoms collected

To get the number of collected ^{11}Be atoms a fit is performed to the 2124keV and 2895keV gamma lines with the function given in equation (2.4). The two gamma lines are used in order to get a consistency check of the data and the calibration. An example of the energy spectrum can be seen at Figure 2.1. Here the 2124keV gamma is clearly seen along with its single and double escape lines. The 2895keV gamma is also seen, however, it is much less prominent.

To get the correct number of atoms collected, it is necessary to correct the number seen in the HPGe-detector for several effects. First of all a correction for the efficiency of the detector should be made. Second, a correction for the period of time in which the 2895keV gamma was not visible in the detector, due to the factor of 2 increase in amplification[1], should be made. This is illustrated in Figure 3.1. Third, a correction for the dead time must be performed. Finally, it is important to use the correct gamma intensities for the decay of ^{11}Be taking into account cascade effects.

First of all the correct gamma intensities are found in the article *J. Phys. G: Nucl. Part. Phys. 40 035109 (2013).* They are given as

$$I_\gamma(2124) = 0.355(18) \tag{3.1}$$

$$\frac{I_\gamma(2895)}{I_\gamma(2124)} = 2.27(8) \cdot 10^{-3}$$

$$\Downarrow$$

$$I_\gamma(2895) = 8.06(50) \cdot 10^{-4} \tag{3.2}$$

The efficiency is easily corrected for, just divide the number of ^{11}Be atoms seen in the detector with the efficiency at the relevant energy.

To get a number for the dead time it is sufficient to look at the number of raw triggers and the number of accepted triggers, and take the ratio between the two. However, this is only true if the events follow a Poisson distribution. To test this, a Poisson distribution has been fitted to the number of raw triggers between two accepted triggers in the HPGe-detector. An example of this for parts of run 49 can be seen at Figure 3.2.

When looking at Figure 3.2 one need to note the fact that this is the only part of the data in which the dead time is at roughly 10 per cent[2], while for the rest of the data it is only about 2 per cent. This is reflected in the fact that a small part of the data does not follow the Poisson distribution. But

[1] See the logbook at page 22-23 and also the section about the energy calibration.

[2] This is only the case at the end of run 49, which is the data shown here.

for the main part of the collection of ^{11}Be, the data nicely follows a Poisson distribution.

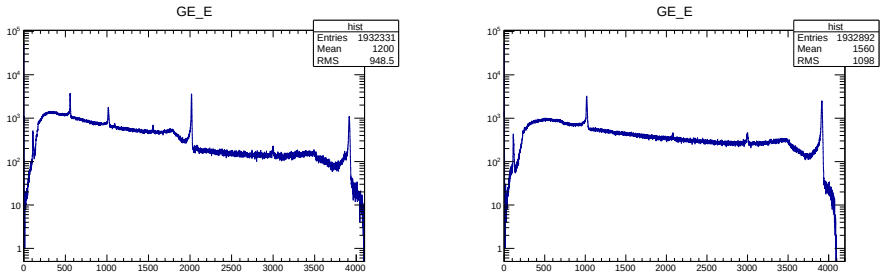

Figure 3.1: *HPGe-detector energy spectra during the ^{11}Be data taking. At the left is the spectrum during the data file where the gain changed by a factor of roughly 2. At the right is the spectrum of the data file taken just after the gain had changed. Compare this with Figure 2.1, which are from just before the gain changed. It is clear that the 2895keV gamma line is missing after the change of gain.*

Therefore, it is sufficient to make a simple average by taking the ratio of the total number of accepted triggers to the total number of raw triggers. This should give a reliable estimate of the dead time. The resulting dead time is only 2.82% with no uncertainty.

The last correction, which is needed, is the one for the missing data for the

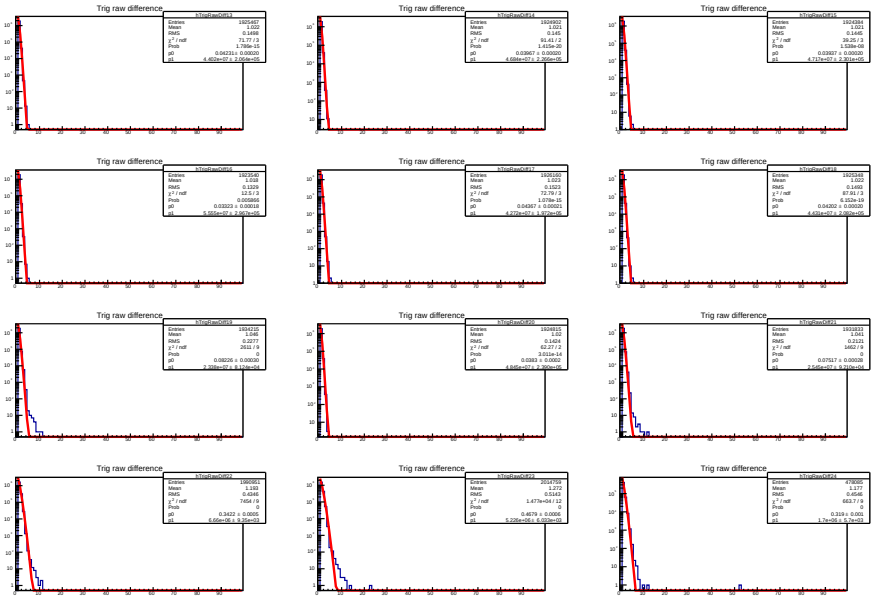

Figure 3.2: *The distribution of the number of raw triggers between two accepted triggers for several files from run 49. A fit with a Poisson distribution is also shown. Note the logarithmic scale on the y axis.*

2895keV gamma. In order to correct for this, it is necessary to look at how many 2124keV gammas are detected during the relevant time, compared to how many 2124keV gammas are detected in total. One minus the ratio between these two numbers should give a reliable estimate for the correction factor. The corresponding correction is 2.06%. This is only a correction to the number calculated with the 2895keV gamma line.

The total amount collected is now given by the parameter for the area of the peak, p_2, divided by deadtime, gamma intensity and efficiency, i.e.

$$\#^{11}\mathrm{Be}(E) = \frac{p_2}{(1 - DT) \cdot I_\gamma(E) \cdot \varepsilon(E)} \tag{3.3}$$

However, for the 2895keV gamma line it is also necessary to divide by $(1-0.0206)$ for the missing data.

Performing this calculation one gets the following result from each of the two gamma lines

$$\#^{11}\mathrm{Be}(2124\mathrm{keV}) = 1.377(34)_{\mathrm{stat}}(55)_{\mathrm{sys}} \cdot 10^{12} \tag{3.4}$$

$$\#^{11}\mathrm{Be}(2895\mathrm{keV}) = 1.538(65)_{\mathrm{stat}}(26)_{\mathrm{sys}} \cdot 10^{12} \tag{3.5}$$

The statistical uncertainties comes from p_2, the gamma intensities, and the efficiency. For the systematic error there is only a contribution from the efficiency. For both systematic and statistical uncertainties no correlation terms have so far been considered.

Finally comes the combination of the two numbers into one by doing a weighted average with a proper description of the combination of errors. As one type of error does not dominate over the other, a proper treatment of both statistical and systematic errors are needed.

Assuming the two values for the number of atoms collected are fully correlated it is possible to write

$$\mathrm{corr}(x, y) = \frac{\mathrm{cov}(x, y)}{\sigma_x \sigma_y} = \begin{pmatrix} 1 & \frac{\mathrm{cov}(x,y)}{\sigma_x \sigma_y} \\ \frac{\mathrm{cov}(y,x)}{\sigma_y \sigma_x} & 1 \end{pmatrix} \tag{3.6}$$

$$\Rightarrow \mathrm{cov}(x, y) = \begin{pmatrix} 34^2 + 55^2 & 55 \cdot 26 \\ 26 \cdot 55 & 65^2 + 26^2 \end{pmatrix} \tag{3.7}$$

using the fact that only systematic uncertainties will be in the off-diagonal elements. In the above the numbers are given in units of 10^9 atoms.

To calculate the weighted mean and the error on the weighted mean, equation 6.23 and 6.24 from *R. J. Barlow, Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences* are used. They are given as

$$\hat{\mathbf{a}} = (\tilde{\mathbf{C}}\mathbf{V}(\mathbf{y})^{-\mathbf{1}}\mathbf{C})^{-\mathbf{1}}\tilde{\mathbf{C}}\mathbf{V}(\mathbf{y})^{-\mathbf{1}}\mathbf{y} \tag{3.8}$$

$$\mathbf{V}(\hat{\mathbf{a}}) = [\tilde{\mathbf{C}}\mathbf{V}(\mathbf{y})^{-\mathbf{1}}\mathbf{C}]^{-\mathbf{1}} \tag{3.9}$$

where $\mathbf{C} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$, $\tilde{\mathbf{C}} = \begin{pmatrix} 1 & 1 \end{pmatrix}$, $\mathbf{y} = \begin{pmatrix} 1377 \\ 1538 \end{pmatrix}$, and

$$\mathbf{V}(\mathbf{y}) = \mathrm{cov}(x, y) = \begin{pmatrix} 34^2 + 55^2 & 55 \cdot 26 \\ 26 \cdot 55 & 65^2 + 26^2 \end{pmatrix}. \tag{3.10}$$

The final result is

$$\#^{11}\mathrm{Be} = \hat{\mathbf{a}} = 1.447(55) \cdot 10^{12} \tag{3.11}$$

number of ^{11}Be atoms collected in the Cu sample. The uncertainty given is the combination of systematic and statistical uncertainties.

4

Number of ^{11}Li atoms collected

In order to understand the beam from the target, we took an 80 minutes run with collection of ^{11}Li in a Cu sample. As mentioned in the proposal we expect some contamination of ^{11}Li on the mass of ^{11}Be due to the low mass difference. As ^{11}Li will also decay into ^{10}Be it is thus a major contaminant and we need to reduce it as much as possible.

This have been done in two ways. First of all by using the HRS mass separator with slits in, to cut away part of the beam. Second, by setting the beam gate to be closed in 150ms after proton impact on target. The half-life of ^{11}Li is 8.75ms, so the main part of the ^{11}Li atoms will have decayed by the time the beam gate is opened.

To fully understand how large the contamination from ^{11}Li is, a separate sample was collected. The HRS was set to the mass of ^{11}Li, and the beam gate was closed for 2ms after proton impact after which it was open for 150ms. In this way long lived contamination was avoided. The lead shielding in front of the HPGe-detector was removed.

The energy spectrum of the HPGe-detector from the 80 minutes run can be seen on Figure 4.1. The two gamma lines from ^{11}Li we are looking for, are the 2124keV (gamma intensity of 8%) and the 3368keV (gamma intensity of 33%). More information about the decay can be found in *H.O.U. Fynbo et al., Nuclear Physics A 736 (2004).*

Looking at Figure 4.1 there are clearly no sign of the decay of ^{11}Li. Looking closer at the 2124keV and 3368keV gammas, see Figure 4.2, we definitely do not see any clear signals.

To make an estimate of how many ^{11}Li atoms is collected, we divide the spectra in Figure 4.2 into three regions, all with the width of the expected peak. Then making an averaged background from the two outer regions, and subtracting this number from the counts in the peak (central) region, we get a number of counts with some statistical uncertainty.

For the 2124keV gamma we get 0 ± 34 counts before corrections are made. For the 3368keV gamma we get 0 ± 42 counts before corrections are made. Correcting for gamma intensity and efficiency[1] we get the following limits

$$\#^{11}\text{Li}(2124\text{keV}) < 4.36 \cdot 10^6 \tag{4.1}$$

$$\#^{11}\text{Li}(3368\text{keV}) < 3.22 \cdot 10^6 \tag{4.2}$$

[1]Here we used the efficiency calculated at the experiment, as there was no lead piece in front of the HPGe-detector, and we only made an offline efficiency calibration with lead in front of the detector.

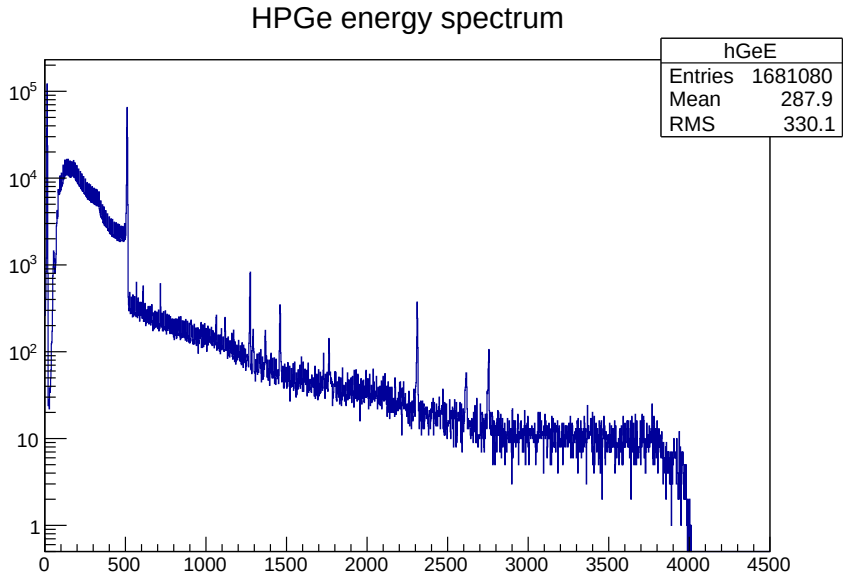

Figure 4.1: *HPGe energy spectrum in keV for the ^{11}Li collection.*

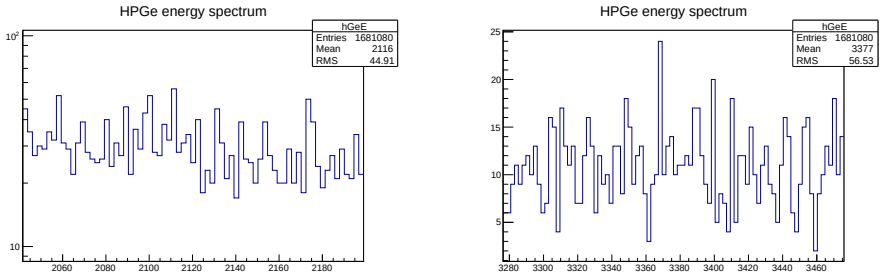

Figure 4.2: *HPGe energy spectrum in keV for the ^{11}Li collection. Left panel shows the region close to the 2124keV gamma line. Right panel shows the region close to the 3368keV gamma line.*

for the number of atoms collected.

It is important to note that to get an upper limit on the number of atoms collected, the lowest possible efficiency should be used. I.e. when correcting for the efficiency the uncertainty have to be subtracted from the estimated absolute efficiency. An uncertainty of 30% on the efficiency have been used.

5

Number of ^{10}Be atoms collected

Just as ^{11}Li is a possible contamination in the beam, directly produced ^{10}Be is also a possible contamination. If this is produced in large amounts we do not have a reliable result for the branching ratio to ^{10}Be.

Therefore a separate sample of ^{10}Be was taken over a period of 1 second with HRS set to the mass of ^{10}Be (see logbook page 38). At Figure 5.1 the current on the Cu plate catcher is shown as a function of time. The large peak is the 1 second implantation of ^{10}Be. To make a rough estimate of the amount of atoms implanted in the Cu plate, we take the maximum current measured and multiplies it with the 1 second time window, to get an upper limit of 3.5pC. This gives a maximum of $2 \cdot 10^7$ ^{10}Be atoms collected.

As ^{10}Be is very long lived, gammas were not expected to be seen.

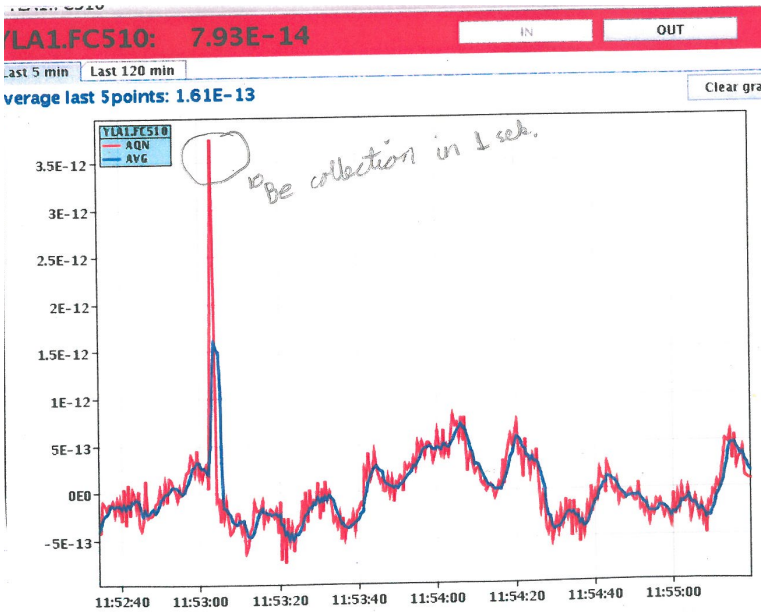

Figure 5.1: *From the ISOLDE e-log (see the IS541 logbook page 38). Screenshot of the YLA1.FC510 Faraday cup which measures the current on the Cu plate in our setup used for collection. The peak shows the 1 second collection of* ^{10}*Be.*

6

Sources

In Table 6.1 an overview of the used sources can be seen describing their activity, measurement time of the activity, and the half-life. In Table 2.1 a list of gamma energies and intensities used can be seen.

Table 6.1: *Data for the three sources used.*

Source	Activity (Bq)	Date	RP ID	Halflife
^{60}Co	44500 ± 890	22$^{\text{nd}}$ of July 1996	3726RP	1925.28(14) d
^{152}Eu	37500 ± 750	12$^{\text{th}}$ of March 1996	3679RP	13.528(14) yr
^{228}Th	587.81 ± 11.76^{a}	5$^{\text{th}}$ of December 2012	4034RP	1.9116(16) yr

[a] No uncertainty is given for ^{228}Th but for both Co and Eu there is an uncertainty of 2% which I assume to be general, and therefore I also apply this to Th.