

Gamma spectroscopy

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Group B

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1 Introduction

The goal of this laboratory class was to measure the gamma radiation emitted by radioactive isotopes. Alpha and beta decays release energy on the order of one up to a couple MeV. Alpha decays are strong processes, meaning they can be described by diagrams involving pion exchanges (at a deeper level this is a result of gluon exchanges, the strong interaction). Beta decays is a result of the weak interaction causing a flavor change ($u \rightarrow d$ in the case of negative beta decay) mediated by the W^\pm bosons. Some of the available energy is carried away by the electrons and neutrinos in beta decays, alpha particles in alpha decays. This process leaves an excited nucleus behind. Gamma photons are emitted as these excited nuclei reach their ground states. Based on the measured spectra both the isotope type and the activity of the isotope can be determined.

1.1 Measurement setup

The two main parts of the measurement setup were the HPGe detector and the amplitude analyzer. HPGe stands for high purity germanium, this makes up the sensitive part of the detector. The rest of the detector consists of protective casing and electronics. Incoming ionizing radiation creates electron-hole pairs. The number of created pairs is to good approximation proportional to the energy absorbed by the semiconductor. The detector is indirectly connected to a liquid nitrogen bath, which cools down the detector considerably. This makes it that thermal fluctuations don't create a significant number of electron-hole pairs, so the only source of current that is measured comes from electron-hole pairs created by the ionizing radiation. These pairs are prohibited from recombining by the high voltage connected to the germanium detector.

The other key component is the amplitude analyzer. It measures the charge carried by electric impulses. This charge is directly proportional to the number of electron-hole pairs created during the time interval of the pulse and therefore characteristic of the energy of the incoming radiation. Based on this charge the amplitude analyzer chooses the corresponding energy bin, and increments the counter corresponding to that bin by one. Finally this analyzer is connected to a computer, where the data is interpreted and displayed. The relation between the bin numbers and the energy of the radiation is expected to be linear, but the exact parameters of the relation are not known before calibration.

2 Calibration

To determine the parameters of the linear relation between bin number and energy, peaks with known energy are needed to be measured. The linear relationship is expected based on reasoning described in the previous paragraph. During our measurement we used ^{232}Th isotope. The energy of two easily identifiable gamma peaks is known. The first one is 238.6keV , this is the peak with the largest intensity. The other characteristic peak is at 2614.7keV , this is the highest energy peak observed. These peaks were identified in the spectrum. To validate the identification of peaks, after using the two peaks to calibrate the linear relation between energy and bin number, other peaks of the ^{232}Th isotope were identified and we checked if their energy matches up with the values read off from tables. These other peaks were at 580keV and 908keV according to the calibration. These are the 583.191keV and 911.316keV peaks respectively, both corresponding to ^{208}Tl , which is part of the thorium series. The linear fit for energy was

$$E = 1.3247\text{keV} \cdot n - 4.6\text{keV}, \quad (1)$$

where n is the bin number. From the validation we know the energy measured from the bin number is accurate within a couple keV . This is precise enough to identify peaks. The source of the error is that the current impulse coming from the HPGe detector isn't exactly in linear relation with the energy absorbed by the detector.

3 Granite sample

The first sample we examined after calibration was a granite rock sample. Table 1. contains the data required for the activity calculations.

Energy [keV]	Net area	Net area rel. error	Intensity	η	η rel. error	Isotope
351.3	36043	0.6%	3.689e-01	2.1975%	9.0%	^{214}Pb
999.1	620	14.2%	5.892e-03	0.8457%	7.6%	^{234}Pa
186.7	12230	1.1%	3.280e-02	3.1371%	9.1%	^{226}Ra
295.0	23525	0.9%	1.919e-01	2.0425%	6.6%	^{214}Pb
1765.1	4430	1.9%	1.620e-01	0.4518%	8.8%	^{214}Bi
1118.6	5706	2.0%	1.550e-01	0.7023%	9.3%	^{214}Bi
242.1	10554	1.7%	7.453e-02	2.6091%	8.7%	^{214}Pb

Table 1: Granite sample data

The spectrum was taken over a period of 1000s. From this the activity can be calculated using

$$A = \frac{N}{I\eta t}, \quad (2)$$

with error

$$\sigma_{\text{rel}}(A) = \sqrt{\sigma_{\text{rel}}(\eta)^2 + \sigma_{\text{rel}}(N)^2}. \quad (3)$$

These equations give the results in table 2.

Energy [keV]	Activity [kBq]	Activity error [kBq]	Isotope
351.3	4.4	0.4	^{214}Pb
999.1	12.4	2.0	^{234}Pa
186.7	11.9	1.1	^{226}Ra
295.0	6.0	0.4	^{214}Pb
1765.1	6.1	0.5	^{214}Bi
1118.6	5.2	0.5	^{214}Bi
242.1	5.4	0.5	^{214}Pb

Table 2: The activities corresponding to peaks in the granite sample.

Corresponding peaks can be averaged. The correct way to calculate the average given that we know the uncertainties is the following,

$$\langle A \rangle = \frac{\sum_i A_i / \sigma_i^2}{\sum_i 1 / \sigma_i^2}. \quad (4)$$

The uncertainty of this averaged number is

$$\sigma_A = \frac{1}{\sqrt{\sum_i 1/\sigma_i^2}}. \quad (5)$$

With the above formula I determined the combined activity of the lead and bismuth isotopes. To determine if a significant fraction of the radon gas escapes the granite sample I also calculated the weighted average of the isotopes before and after the radon in the decay chain. Only the radium and protactinium peaks correspond to isotopes which are before radon in the decay chain. The results are summed up in table 3. and in figure 1.

Group	Activity [Bq]	Activity error [Bq]
^{214}Pb	5282	244
^{214}Bi	5614	367
Before ^{222}Rn	12012	957
After ^{222}Rn	5384	203

Table 3: Averaged activities of the granite sample

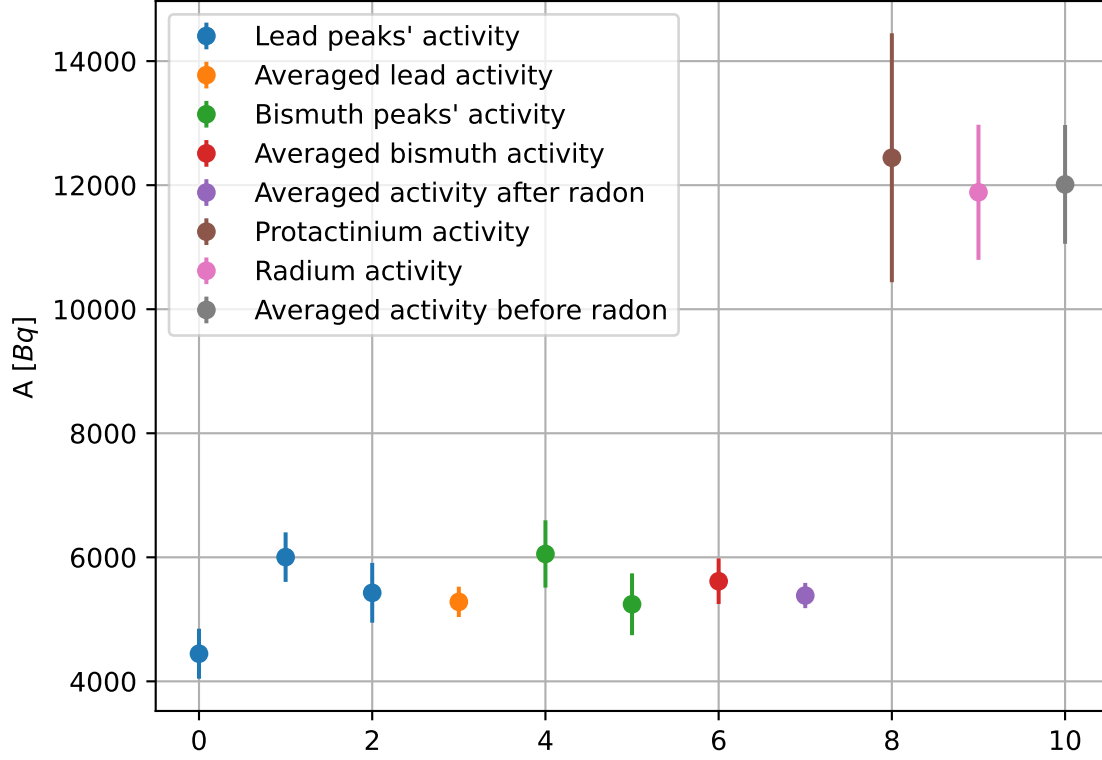


Figure 1: Graphical representation of activities and errors corresponding to peaks and their averages.

From figure 1. it can be seen that the error in the activity corresponding to the 186keV radium peak and the 1001keV protactinium peak is large compared to their difference. This means the amount of ^{235}U , which would contribute to the 186keV peak can not be determined from this measurement. 0.7% ^{235}U contributes

$$\frac{0.7\%\lambda_{235}}{0.7\%\lambda_{235} + 99.3\%\lambda_{238}} = 4.3\% \quad (6)$$

to the 186keV peak. The relative error in the activity of the 186keV peak is 9.2% and 16.1% for the 1001keV peak. The intensity corresponding to the ^{235}U is roughly 16 times larger compared to the 186keV emission of ^{226}Ra . Based on these numbers a rough estimate for the most amount of ^{235}U consistent with the measured data is $\sqrt{9.2\%^2 + 16.1\%^2}/4.3\%/16 = 0.27\%$. However this does not account for any systematic errors. One possible error I could think of is that the region of interest selected was too

small for the $186keV$ peak. The region of interest was from $184.85keV$ to 188.82 , the FWHM was $2.04keV$ and the centroid $186.69keV$. Based on this data at least some of the error is likely explained by a too small region of interest, as for other peaks the region width and FWHM ratio was higher. Other sources of error could be unaccounted differences in μ , as the the Monte-Carlo simulation did miss some of the details of the setup.

With more precise data the ^{235}U content could be calculated the following way. The activity of protactinium and radium is the same as they are both isotopes before radon in the decay chain. However the $186keV$ peak corresponding to radium gets contribution from the decay chain of ^{235}U . Based on the difference the ^{235}U content can be determined. It is important that the difference is taken between the measured and expected net areas. This is because the intensity corresponding to the $186keV$ peak is different for radium and the ^{235}U decay chain. Following this logic, the expected net area corresponding to ^{226}Ra is

$$N_{Ra-226} = N_{Pa-234} \frac{I_{Ra-226}\mu_{186keV}}{I_{Pa-234}\mu_{1001keV}}. \quad (7)$$

μ are the detector efficiencies at the peak energies, while I are the intensities (probabilities) corresponding to the relevant photons. These μ and I values are listed in table 2. The difference gives the net area corresponding to the $186keV$ peak of ^{235}U ,

$$N_{235} = N_{186keV} - N_{Ra-226}. \quad (8)$$

Here N_{186keV} corresponds to the measured net area of the $186keV$ peak, N_{Ra-226} is calculated with the previous formula. Finally N_{235} is the net area corresponding to ^{235}U . Using (2) the activity of ^{235}U is

$$A_{U-235} = \frac{N_{235}}{I_{U-235}\mu_{186keV}t} = \frac{N_{186keV}}{I_{U-235}\mu_{186keV}t} - \frac{I_{Ra-226}}{I_{U-235}} \frac{N_{Pa-234}}{I_{Pa-234}\mu_{1001keV}t}. \quad (9)$$

This gives ^{235}U content of $m_{235} = (-0.0004 \pm 0.0017)g$. Obviously the isotope content of a sample can't have negative mass, meaning based on this calculation the expected ^{235}U content of the sample is between $0g$ and $0.0013g$. This calculation does not account for possible sources of errors mentioned in the previous paragraph either, the main suspect being a too narrow selection for the region of interest around the $186keV$ peak.

Based on the averaged activity before and after the radon, we can estimate the amount of radon gas that escapes the rock sample before decaying.

$$r = \frac{A_1 - A_2}{A_1}, \quad (10)$$

where r is the ratio of radon gas that escapes before decaying, A_1 and A_2 are the averaged activities measured from elements before and after the radon in the decay chain, respectively. The error of this ratio is given by

$$\sigma_r = \sigma \left(1 - \frac{A_2}{A_1} \right) = \frac{A_2}{A_1} \sqrt{\left(\frac{\sigma_{A_1}}{A_1} \right)^2 + \left(\frac{\sigma_{A_2}}{A_2} \right)^2}. \quad (11)$$

The result of this calculation is that $(55.2 \pm 4.0)\%$ of the radon gas escapes the granite sample before decaying.

From the activity of the isotopes before the radon gas the amount of ^{238}U can be calculated using its decay rate. This is because those isotopes are guaranteed to be in secular equilibrium granted the rock formed sufficiently long ago.

$$N = \frac{A}{\lambda}, \quad (12)$$

$$\sigma_N = \frac{\sigma_A}{\lambda}, \quad (13)$$

where $\lambda = \frac{\log(2)}{T_{1/2}} = 4.92 \cdot 10^{-18} \frac{1}{s}$ is the decay rate of ^{238}U . From this the number of ^{238}U atoms in the granite sample is $(2.44 \pm 0.19) \cdot 10^{21}$, which corresponds to a mass of $(0.966 \pm 0.077)g$ ^{238}U in the granite sample. Knowing that the mass of the granite sample was $280g$, the ^{238}U concentration of the sample is $(3450 \pm 270)g/ton$.

4 Soil sample

The data of the measured peaks from the soil sample are summarized in table 4.

Energy [keV]	Net area	Net area rel. error	Intensity	η	η rel. error	Isotope
658.5	407	5.7%	8.998e-01	1.1082%	8.6%	^{134}Cs (^{134}Ba)
120.9	437	6.6%	2.843e-01	3.3051%	7.7%	^{152}Eu
343.4	172	9.9%	2.649e-01	1.6480%	8.2%	^{152}Eu
1405.3	27	22.8%	2.075e-01	0.4523%	8.9%	^{152}Eu
776.7	50	22.4%	1.274e-01	0.9176%	8.9%	^{152}Eu
244.9	65	14.6%	7.494e-02	2.5473%	9.5%	^{152}Eu

Table 4: Soil sample data. The 658.5keV peak is emitted by ^{134}Ba after a ^{134}Cs beta decays.

The first peak is emitted by a transition of the barium atom, after a cesium atom decays into it. The activities can be calculated in the same ways as for the granite sample. The results are listed in table 5.

Energy [keV]	Activity [kBq]	Activity error [kBq]	Isotope
658.5	44.8	4.6	^{134}Cs (^{134}Ba)
120.9	51.0	5.2	^{152}Eu
343.4	43.3	5.5	^{152}Eu
1405.3	31.6	7.7	^{152}Eu
776.7	46.9	11.3	^{152}Eu
244.9	37.4	6.5	^{152}Eu

Table 5: The activities corresponding to peaks in the soil sample. The $658.5keV$ peak is emitted by ^{134}Ba after a ^{134}Cs beta decays.

Averaging the europium peaks' activities as in the case of the granite sample I got $(43.2 \pm 2.9)Bq$. These activities are visually represented by figure 2.

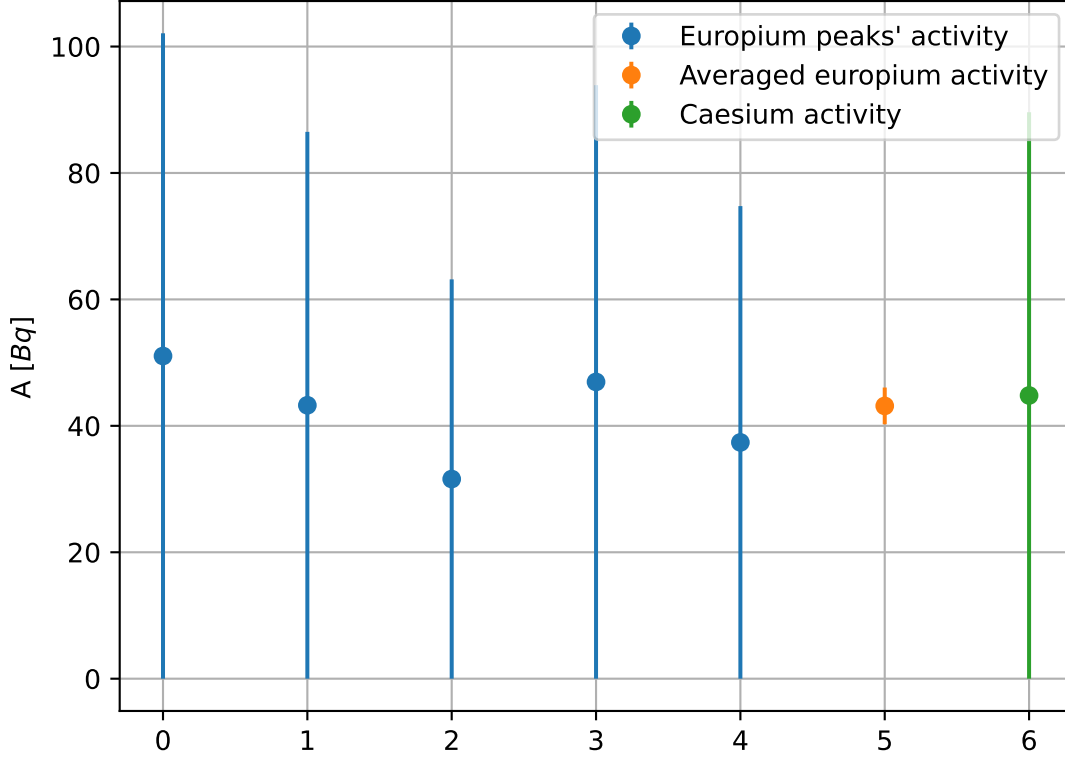


Figure 2: Graphical representation of activities and errors corresponding to peaks and their averages.

5 Conclusion

The lab introduced us to gamma spectroscopy and analyzing the data obtained. In the first part we calibrated the measurement with a thorium sample. The next part was about taking the spectrum of a granite sample and identifying the peaks seen. During evaluation I concluded that a significant portion of the radon gas escapes the sample. The uranium-235 concentration estimated based on the 186keV and 1001keV peaks is lower than expected. A possible source of this error could be the incorrect selection of the region of interest around the 186keV peak. The FWHM to region width ratio was 1.2-2 times as high for the 186keV peak as for the other peaks. I also determined the uranium content of the sample. Finally I repeated some of the calculations for a soil sample from near a

nuclear bomb test.