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Lab Report
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Measuring ^{40}K Activity in Soil

Abstract

Measuring the activity per gram of Potassium-40 in two samples at the DePauw Nature Park. The two samples are taken from the Woodland trails (W2) and the Quarry trials (Q2). The two samples are then made uniform and spiked with table salt containing natural potassium and Potassium-40. At each stage of the measurement, the soil samples are placed in front of a NaI(Tl) Scintillator to detect the gamma rays of Potassium-40 coming of each sample. Then the data is transferred into a gaussian fit curve to find the activity per gram of each sample. The activity per gram of Q2 and W2 turn out to be are $6.22\text{E-}02 \pm 1.86\text{E-}02$ Bq/gram, and $1.40\text{E-}01 \pm 3.19\text{E-}02$ Bq/gram respectively, where W2 has more Potassium-40 than Q2.

Introduction

The DePauw Nature Park is situated in a once active limestone quarry. From this location, the group took two soil samples from different areas of the park to test the activity per gram of Potassium-40 in the soil. Potassium-40 (^{40}K) is a radioactive isotope with a half-life of 1.25 billion years and makes up 0.0117% of potassium found in nature. The reasoning for testing the activity of Potassium-40 in soil is to see which of the two samples from different areas has the most Potassium-40 present in their soil. The two samples are taken from the Woodland Trails (W2), and the Quarry Trial (Q2). The samples used here are from 2019. Using a NaI(Tl) Scintillator, the group will measure the radioactivity within each sample; its background radiation, its natural raw radiation, and its radiation when spiked with table salt containing Potassium.

Procedure

There were two soil samples used for the experiment both taken from the DePauw Nature Park in Greencastle, Indiana. The two samples were taken from the Quarry Trail (Q2), and the Woodlands Trails (W2). The soil samples were gathered using a small shovel. For each sample, the group walked onto each area, and off the side of the trail dug a hole using the small shovel, put the soil into a plastic bag, and sealed it. Once both samples are collected, the group returned back to the lab and sifted through the soil samples to remove any stones or other materials that may interfere with the radiation tests. After the samples were cleaned, the soil was put into a mortar and pestle to grind it down into a uniform consistency. From there the weight of each sample was taken on a triple beam balance first by measuring the mass with error of the jar that the sample would be placed into, and then taking the mass with error of the jar with the soil sample in it. This was done by taking multiple measurements of the jar and jar with soil then subtracting the average mass of the jar from the mass of the jar with soil. The error was then found by adding the squares of each mass error, then taking the square root of that product. The mass of the soil for Q2 used was 522.27 ± 0.24635 grams and for W2 the soil sample is 522.3975 ± 0.070711 grams. Next, the group used table salt to spike the soil sample to bring out the measurements of Potassium-40. As mentioned before Potassium-40 makes up 0.0117% of potassium found in nature. Similar to this table salt, the ratio of Potassium-40 to natural potassium was .350g to 1.4g, which means the percent of natural potassium in the spike was $\frac{1}{4}$ or

25% of the spike size. The spike size for Q2 was 71.978 ± 0.13266 grams, and the spike size for W2 was 75.1375 ± 0.070711 grams.

During each step of the process, there were three measurements taken for each sample for a total of six measurements, these were the background measurement, the non-spiked soil measurement, and the spiked soil measurement for each sample. This was obtained from using a NaI(Tl) Scintillator for each test. The NaI(Tl) Scintillator works similarly to a multichannel analyzer.

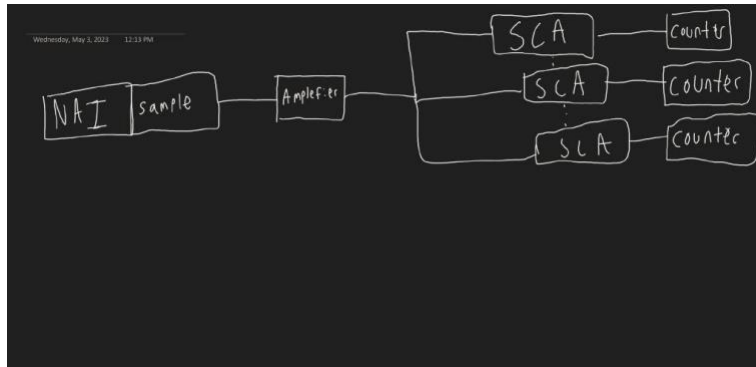


Figure 1: Diagram of Multichannel Analyzer

As the name suggests and from the diagram above the sample is placed in front of the analyzer where the Sodium-Iodine (NaI) sample is. From there the radiation measurements are taken and pass through an amplifier each then lead to multiple single channel analyzers (SCA). These SCA then send the information received from the amplifier into separate counters or channels. From there each channel displays a different voltage/measurement of the sample and translates it into the form of a histogram which is the samples spectrum. Further, the NaI portion of the detector serves to respond to the gamma rays produced by the sample. This is done by a small flash of light or scintillation is produced by the NaI detector, and the electrons in the NaI sample return to their ground state. For our data the spectrum relates to the number of counts in each channel for a total of around 8100 channels. For our research purposes, the group will be looking at the channels between 6000 and 6400 which correlate to the 1460 Kev gamma ray peak of Potassium-40. Each sample produced a livetime, or the amount of time the detector was running for. For each Q2 measurement the livetimes were 588320 seconds, 588451 seconds, and 599413 seconds for background, non-spiked, and spiked measurements. Then for W2 the livetimes were 95863 seconds, 239343 seconds, 200360 seconds for the same measurements.

Data & Analysis

The final measurement for the activity in the soil is measured using activity per gram of the sample which is found by

$$\alpha = \frac{A_{Soil}}{M_{Soil}} \quad \text{Eq.1}$$

Where α is the special activity in Becquerels (Bq) per grams, A_{Soil} is the activity of the soil, and M_{Soil} is the mass of the soil sample in grams. From there the group can then get the error of the special activity from the equation

$$\sigma_{\alpha} = \sqrt{\left(\frac{\sigma_{A_{Soil}}}{A_{Soil}}\right)^2 + \left(\frac{\sigma_{M_{Soil}}}{M_{Soil}}\right)^2} \quad \text{Eq.2}$$

Where σ_α is the error in special activity, and $\sigma_{A_{soil}}$ is the error in the activity of the soil, and $\sigma_{M_{soil}}$ is the error in the mass of the soil. The special activity is first obtained by finding the rate of gamma rays in the soil sample, which is defined by

$$R = A[f\epsilon_{SA}\epsilon_S\epsilon_{det}] \quad Eq. 3$$

Where R is the rate of gamma rays, f is the natural abundance of Potassium-40, and ϵ_{SA} is the soil angle, ϵ_S is the soil absorption, and ϵ_{det} is the probability of detection in the NaI(Tl) Scintillator, and A is the activity for the soil. From here we further derive the equation to solve for A, after we solve for A we are left with the equation for the activity in the soil

$$A_{soil} = (R_{raw\ soil} - R_{bck}) \frac{A_{spike}}{(R_{spike\ soil} - R_{raw\ soil})} \quad Eq. 4$$

From here we obtain the activity value used in equation 1, where A_{spike} is the activity in the spiked soil, and the R values represent the rate of gamma rays in each of the six measurements. The special activity for Q2 is $6.22E-02 \pm 1.86E-02$ Bq/gram, and for W2 is $1.40E-01 \pm 3.19E-02$ Bq/gram.

For the activity in the soil measurements the spike activity is needed, which can be found by the equation

$$A_{soil} = \frac{CA}{B} \quad Eq. 5$$

Where A,B, and C are variables used to denote different values taken from the data. A is defined as $A = R_{Raw\ Soil} - R_{Bck}$ which is the rate of the non-spiked soil sample minus the rate of the background measurement. Similarly, the value for B is found by $B = R_{Soil\ Spike} - R_{Raw\ Soil}$, where $R_{Soil\ Spike}$ is the rate of the spiked soil. As for C, the equation is as follows

$$C = A_{spike} = \lambda A_o e^{-\lambda(t-t_0)} \quad Eq. 6$$

Here C is described as the activity in the spike, and λ is the decay constant of Potassium-40, and $t - t_0$ is the time interval. A_o is the initial activity. Since we know the half-life is 1.25 billion years, we can calculate the decay constant to be $1.76E-17$ 1/sec. With the decay constant being so small, the exponential $e^{-\lambda(t-t_0)}$ is negligible, therefore we can treat this function as zero. The value A_o is dependent on N_o , which is the number of nuclei present at the beginning of the measurement before decay. N_o is found by

$$N_o = \frac{m_s f_k f_{40k}}{M_a} N_A \quad Eq. 7$$

Where N_A is Avogadro's Number, M_a is the atomic mass of Potassium-40 (40g), m_s is the mass of the salt used for the spike, f_k is the fraction of salt that is natural potassium, and f_{40k} is the natural abundance of Potassium-40. Therefore, the new equation for C is

$$C = \lambda N_o. \quad Eq. 6$$

The error for C is the obtained through the equation

$$\frac{\sigma_C}{C} = \sqrt{\left(\frac{\partial \lambda}{\partial C}\right)^2 (\sigma_\lambda)^2 + \left(\frac{\partial N_o}{\partial C}\right)^2 (\sigma_{N_o})^2} \quad Eq. 8$$

Where σ_λ and σ_{N_o} are errors in the decay constant, and N_o respectively. The values for C with error for Q2 and W2 are $3.17E+19 \pm 5.84E+16$, and $3.31E+19 \pm 3.11E+16$ respectively.

From here we can plot the graphs from the detector in RStudio, the following graph is for the non-spiked/raw soil samples from Q2 and W2.

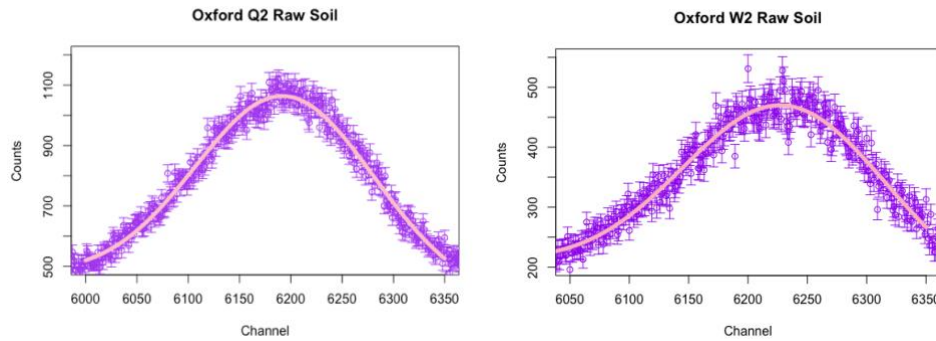


Figure 2: Graphs of Bell curve with Gaussian Fir or Q2 and W2, the channels are from 6000 to 6350 for Q2, and from 6050 to 6350 for W2.

As seen in the graphs, the channels shown are from 6000 to 6350, this spectrum is able to show the 1460 Kev gamma ray peak of Pottasium-40 most accurately. This range is used for all graphs. To fit the spectrum, a gaussian function was used to fit the bell curve of the graph for all six measurements.

The gaussian equation used to fit the curve is

$$a * \exp(-(x - c)^2 / (2 * b^2)) + d * x + e \text{ Eq. 9}$$

Where x is the number of the channel used in the graph, a is the peak of the bell curve, b is the distance from the apex of the bell curve to either end, c is the apex of the bell curve, and d and e are constants defined by the gaussian fit. From each variable we were able to find the area and error of the curve, as well as the rate and error of the graph.

The area and its error are obtained using the following equation

$$\text{Area} = ab\sqrt{2\pi} \text{ Eq. 10}$$

$$\sigma_{\text{Area}} = 2\pi\sqrt{b^2\sigma_a^2 + a^2\sigma_b^2} \text{ Eq. 11.}$$

The peak and error were then obtained by dividing the Area and its error by the livetime of each measurement. The final measurement taken was the reduced chi squared value for each fit, which indicates how well the gaussian curve fits the data, which is found by

$$\chi^2 = \frac{\text{dof}}{\text{sum of squares}} \text{ E. 12}$$

Where dof stands for degrees of freedom, which are the maximum number of independent values in the set, and the *sum of squares* is weighted residual sum-of-squares, which are the sum of all squared values in the set. The closer the chi squared value is two one, the better the fit will be. For these two graphs of Q2 and W2, the chi squared is 1.005 and 1.058 respectively. The values indicate that Q2 has a better gaussian fit then W2 since it is closer to one.

The same procedure is used for the spiked and background measurements of the soil sample. The following are for the graphs of the background and spiked soil sample.

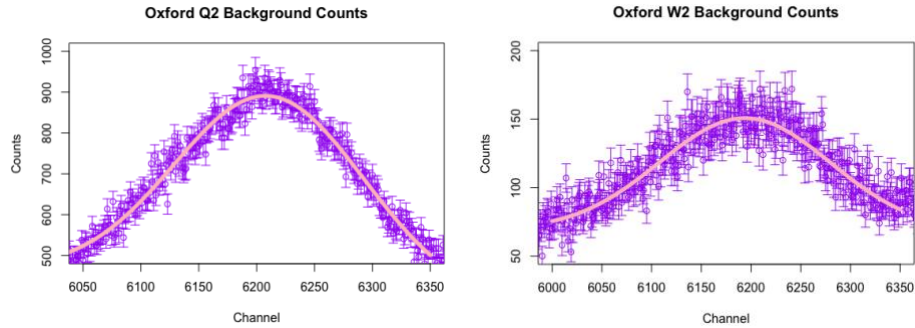


Figure 3: Q2 and W2 graph of Background counts. Q2 is from 6050 to 6350, and W2 is from 6000 to 6350.

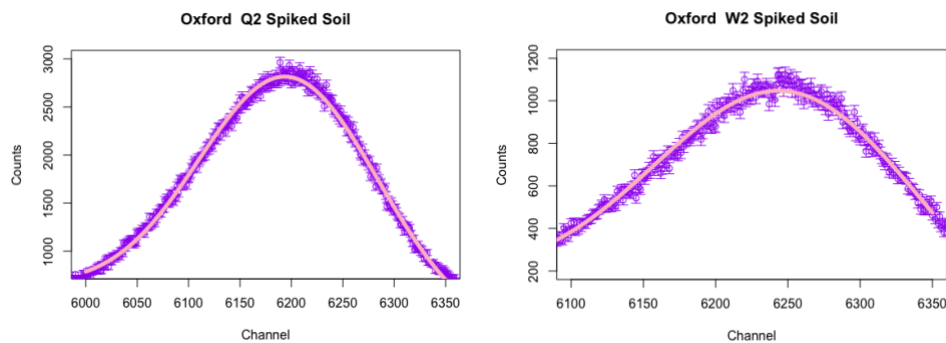


Figure 4: Q2 and W2 of spiked soil. Q2 is from 6000 to 6350, and W2 is from 6100 to 6350.

For the background counts of Q2 the chi squared was 0.964, and for W2 it was 1.047. For the spiked counts, Q2 was 1.32 and W2 was 1.24. Q2 still had a better fit than W2 by a very small amount, but W2 had a better fit when it came to the spiked soil.

Discussion

As stated previously, the activity per gram of Q2 and W2 are $6.22\text{E-}02 \pm 1.86\text{E-}02$ Bq/gram, and $1.40\text{E-}01 \pm 3.19\text{E-}02$ Bq/gram respectively. W2 has a larger activity per gram by a factor of 10. The Q2 sample collected did seem to have a lot of access debris in it compared to W2 and given that Q2 sample is closer to the limestone quarry, it is possible that Potassium-40 is not the most abundant in that area. Further, the livetime for the Q2 sample was much longer than the livetime for W2. This indicates that the Q2 sample was left in front of the detector for a longer period of time. While the larger time can later affect the calculations, the Q2 sample was most likely left for a longer time in front of the detector because it needed more time for Potassium-40 to be detected. Whereas the W2 sample needed less time in front of the detector because Potassium-40 was more abundant there. To further back this theory, all Q2 measurements had a much bigger area than W2, but their rate values were much smaller than that of W2. Having a larger area makes sense because there are more data points to consider, but the higher rate indicates that there are more Potassium-40 gamma rays being detected by the NaI(Tl)

Scintillator indicating that W2 has more Potassium-40 in its sample than Q2, but Q2 has better gaussian fits than W2.

Conclusion

Through the research conducted at DePauw Nature Park, it has been shown the Woodland Trails (W2), have more Potassium-40 present in that area than in the Quarry Trails (Q2). The Quarry Trail had less Potassium-40 likely due to the fact that it is closer to the limestone quarry at the park, and probably had other isotopes present that outweighed Potassium-40. To further prove strengthen this theory, it would be beneficial to go back to the nature park to get another sample of Q2 and test it for other isotopes using the same methods provided here.