Low Budget Gamma Spectroscopy

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Preprint: This article has been submitted to the European Journal of Physics. This preprint is the article before peer review.

Abstract

We describe gamma spectroscopy experiments with an NaI-detector for the student laboratory that can be carried out with moderate expense and without licensed radioactive sources. For calibration, thoriated welding rods and potassium cloride are used, both of which are freely available for purchase. In addition, lead shielding, a costly and hard to handle part of the equipment in radiation lab experiments, is not required. The students analyze the gamma radiation from bulk soil samples they collect themselves, making this a meaningful measurement and a radiation physics experiment accessible to everyone without the usual safety restrictions.

1 Introduction

Gamma spectroscopy experiments are a valuable exercise in undergraduate physics and engineering laboratories [1, 2]. They offer students the opportunity to learn about detector calibration and to perform measurements of environmental gamma radiation, and they illustrate and supplement material on nuclear physics covered in the classroom. However, the cost of equipment

and materials for such an experiment may be prohibitively high for a department or institution that does not have a nuclear physics laboratory . In addition, the radioactive isotopes commonly used generally require special licensing, a hurdle that neither instructors nor teaching institutions may be willing to deal with. In this article, we describe gamma spectroscopy experiments that can be carried out with moderate expense and without any requirements for licensing or concerns for student health. The main purchase is a 2 inch gamma detector, which can be obtained for between $2000 - 5000$ dollars. Lead schielding is not required, as the bulk environmental samples serve two functions: as a radioactive source to be analyzed, and as the shielding against ambient background radiation. The gamma sources we use for calibration are thoriated welding rods, KCl, and fiestaware, all of which are available without restrictions in a store or via the internet. The methods of calibration and analysis we use are similar to those of Ref.1.

The students bring in their own soil samples from different areas of Bavaria, Germany. Since Bavaria received fallout from the Chernobyl nuclear power plant accident in 1986, radioactive contamination of the soil is still of interest today, and the experiment has particular relevance for the students.

We first describe the experimental setup, then discuss how the students calibrate the detector for energy and efficiency. Finally, we list some of the experimental results.

2 Experimental Setup

The main component of our experimental setup is a NaI gamma spectrometer system from gammaspectacular [3], the GSB-2020-NAI Spectroscopy Kit with a 2.0 inch NaI(Tl) Detector. Our main source for energy calibration are thoriated welding rods. To get a strong enough signal, we use two packages with a total of twenty tungsten rods, taped equally spaced around the detector. These contain 2% ^{232}Th, resulting in an activity for the ^{232}Th of around $0.66\mu\, Ci$. Alternatively, one could also use a thoriated lantern mantle. The two other energy calibration sources we use are a bucket of around 5 kg of pure KCl and a fiestaware salt shaker. Fiestaware was manufactured less than 100 years ago with natural uranium. Hence, the ^{238}U decay series has not evolved past ^{234}U and does not contribute significant gammas above 92 keV to the spectrum. However, the gamma at 185.7 keV from ^{235}U is

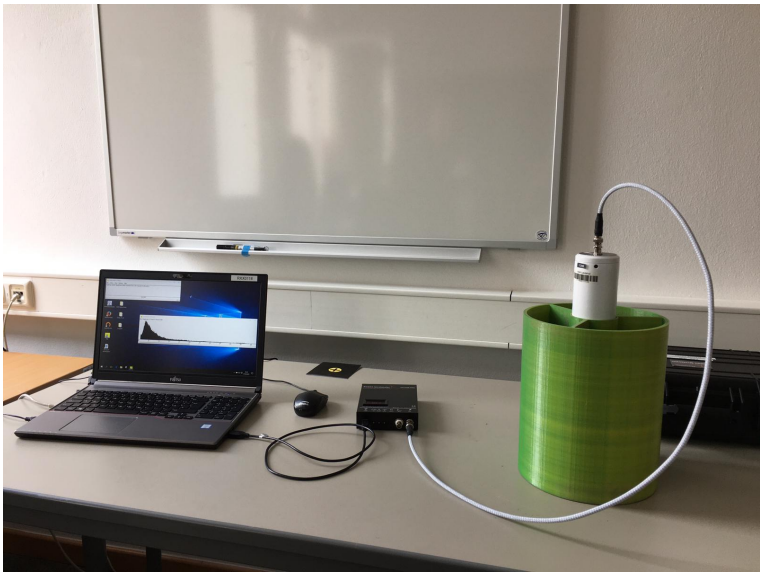

Figure 1: Setup for measuring the soil sample. The height of the soil level in the cylinder is the same as the diameter, 20 cm.

clearly observable.

The students measured three bulk samples in their experiments: a soil or environmental sample, KCl, and NaCl. Each of these bulk samples are put in identical containers. These were produced with a 3-D printer in such a way that the NaI crystal could easily be placed at the center of the bulk sample for maximum efficiency. Fig. 1 shows a container with a soil sample, with part of the white detector sticking out. The NaI crystal itself is a cylinder located at the end of the detector, with a diameter of 2 inch that equals its height. This is a special cylinder shape that gives maximum volume for a given surface area, a fair approximation to a sphere. For this reason, we choose the outer surface of the sample to also be a cylinder whose diameter of 20 cm equals its height. Hence, our sample has the same shape as the NaI crystal scaled up by a factor of around four.

3 Detector Calibration

An important aspect of our student lab experiment is the calibration of the detector for energy and efficiency. For the energy calibration, we use three

Table 1: Relevant gammas from ^{232}Th decay series, ^{40}K, and ^{235}U used for calibrating the detector. The yields for the three isotopes in the ^{232}Th decay series are per ^{232}Th decay at secular equilibrium. The data are from Ref. 8.

Isotope	E_γ (keV)	Yield
^{228}Ac	338	0.113
	911	0.258
	969	0.158
^{212}Pb	239	0.436
^{208}Tl	583	$(0.359)(0.845) = 0.303$
	2614	$(0.359)(0.998) = 0.359$
^{40}K	1461	0.1069
^{235}U	185.7	0.57

sources: 300 g of thoriated welding rods (six energies), 5 kg of KCl (one gamma at 1461 KeV), and a sample of Fiestaware (one gamma at 186 keV), as shown in Table 1. The spectrum for the welding rods is shown in Fig. 2. For the energy calibration, we use the single energy peaks at 238 keV, 338 keV, 583 keV and 2614 keV. In addition, we fit the double peak at 911 keV and 969 keV. The KCl sample provides a peak at 1461 keV, and the Fiestaware a peak at 186 keV. To determine the peak center and area, we use the Gaussian peak fitting method described in Refs. 1, 4. In Fig. 3 we plot these eight energies as a function of bin number. As seen in the figure, the gamma energy is a linear function of bin number.

To calculate the energy dependence of the detector's efficiency, we use the methods of Refs.1, 5. For a gamma of energy E, the count rate C is related to the activity A through the empirical formula [6, 7]

$$C = AY\epsilon(E_{Ref})\left(\frac{E}{E_{Ref}}\right)^b, \tag{1}$$

where $\epsilon(E_{Ref})$ is the detector efficiency for a gamma of energy E_{Ref}. For our soil sample measurements, we will take the reference energy E_{Ref} to be 1461 keV, the energy of the gamma emitted by ^{40}K, and label $\epsilon(E_{Ref})$ as ϵ_{1461}.

To determine the exponent b in Eq. 1, we use the welding rod sample

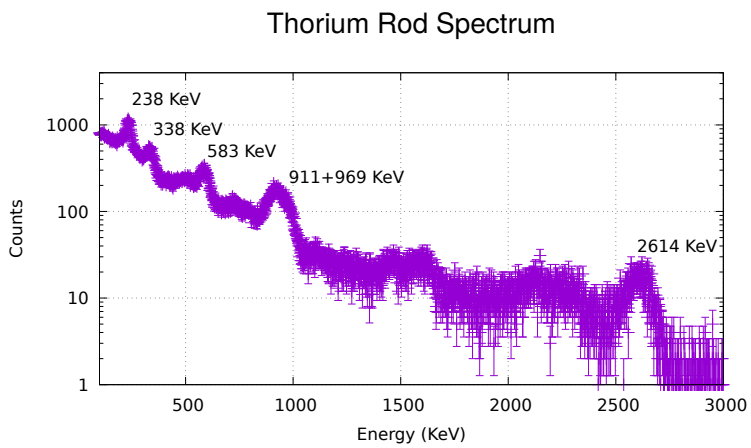

Figure 2: Gamma spectra of the thoriated welding rods. The energies of the gammas used in calibrating the detector are labeled in the figure.

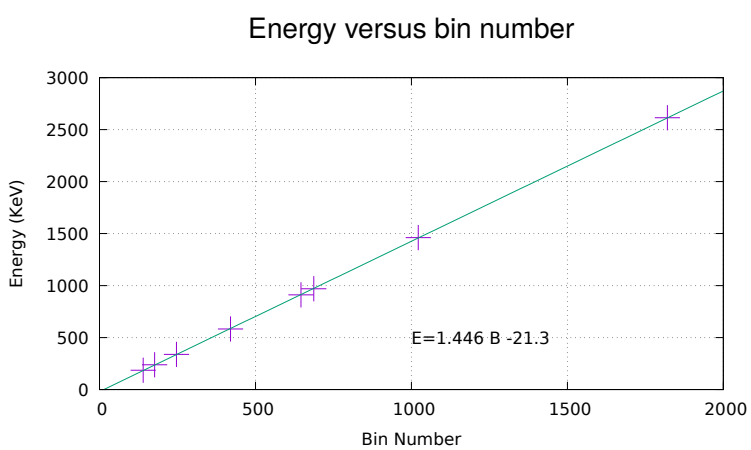

Figure 3: Graph of gamma energy versus bin number. The equation is a linear fit of energy E and bin number B.

which contains the isotope ^{232}Th. Since the gammas from the soil sample will be above 1400 keV, we consider the four highest energy gammas from the welding rods. From Eq. 1, the ratio C/Y is proportional to $A \cdot E^b$. To verify that the energy dependence of Eq. 1 is valid and to determine b, we need to measure the count rate C for gammas from isotopes that have the same activity. Examining the ^{232}Th decay series, we see that the 911 keV and the 969 keV gammas are decay products of ^{228}Ac. The two gammas with energies 583 keV and 2614 keV are products of ^{208}Tl.

In Fig. 4 we plot $log(C/Y)$ versus $log(E)$ for the four highest energy gammas from the welding rods. We have varied three parameters, the activities A_{Ac228} of ^{228}Ac and A_{Tl208} of ^{208}Tl as well as b for a best fit to the data [9]. The common exponent b is equal to -1.12, consistent with the value found in Ref. 1. Since our welding rods are only one year old, the activity A_{Tl208} is around half the activity A_{Ac228}. Note, that if the ^{232}Th decay series is in secular equilibrium, then A_{Tl208} will equal A_{Ac228} and the four gammas will lie in a straight line in a log-log plot of C/Y versus E [5]. The students can also use the ratio A_{Tl208}/A_{Ac228} to "radioactive date" the age of the welding rods [5].

The efficiency ϵ_{1461} and the exponent b in situ will depend on the geometries of detector and sample and on the density of the sample. In the next section, we discuss how our students obtain values of these calibration constants for their soil sample analysis.

4 Soil Sample Analysis

The soil sample analysis is the main goal of the experiment. The soil has a dual role: as a sample to measure environmental radiation, and as shield against the ambient backround radiation in the lab room. Our students took three 20 hour long measurements of bulk samples placed in the cylindrical containers shown in Fig.1: NaCl to determine the ambient background, KCl to determine ϵ_{1461}, and the soil sample. Both the NaCl and KCl have a mass of around five kg and approximately the same density. Since there are no radioactive isotopes in the NaCl sample, the NaCl spectrum gives the students an estimate of the ambient background in the lab room with approximately the same shielding as provided by the soil sample itself. In Fig. 5, we plot a 20 hour spectrum each of the soil sample and the NaCl sample. The difference in the two plots are the counts from the soil sample

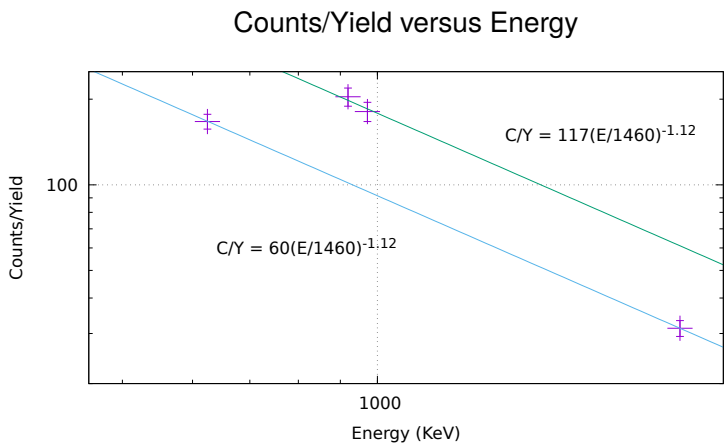

Figure 4: A log-log plot of the Counts/Yield versus gamma energy for thoriated welding rods sample. Data were collected for 15 minutes.

alone.

As in Refs. 1, 5, the students determine the calibration constant ϵ_{1461} by measuring a sample of potassium chloride, KCl, in a container filled with the same volume as the soil sample. That is, both the soil and the KCl sample have the same detector-sample geometry. Using the natural abundance of ^{40}K, which is 0.000117, the students first calculate the activity of the KCl sample. Then, the constant ϵ_{1461} is determined from a measurement of the count rate. For example, our KCl sample has a mass of 5000 g for which the number of ^{40}K nuclei is $N_{\mathrm{K40}} \approx (5000/74.55)(6.02 \times 10^{23})(0.000117) \approx 4.72 \times 10^{21}$ nuclei. The activity of ^{40}K in the sample is determined from $A_{\mathrm{K40}} = N_{\mathrm{K40}} ln(2)/\tau$, where τ is the half life of KCl and equal to 1.248×10^9 years. In our case $A_{\mathrm{K40}} \approx 81200$ Bq. The yield for ^{40}K to emit a 1461 keV gamma is 0.1069. Thus, the rate of 1461 keV gammas emitted by our KCl sample is around 8680 gammas/s. The students record the KCl data for 15 minutes. The mesured count rate minus background from the NaCl data for the 1461 keV photopeak of the KCl sample was 17950 counts/(900 sec), which gives $\epsilon_{1461} \approx 0.0023$.

The final parameter to determine is the exponent b_{situ} in situ, meaning when the radioactive isotopes are in the soil and the shielding due to the soil has therefore to be taken into account. In the initial measurement of b, there was no soil sample present. We refer to this value of the exponent as b_0, i.e. the exponent measured without soil shielding. Gamma attenuation in

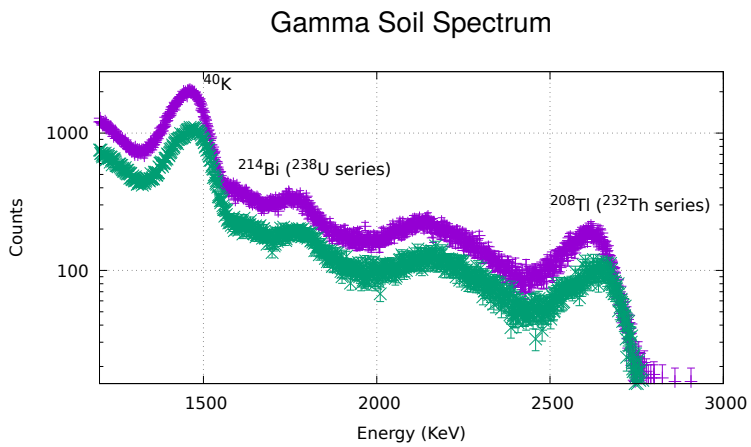

Figure 5: A graph of the gamma spectra of a soil sample (purple points) and a NaI sample (green points). The data were collected for 20 hours.

the soil material is energy dependent, with gammas of lower energy absorbed more strongly than higher energy gammas. This results in a less negative value for b [1]. To estimate b_{situ}, the students measured the radiation when the welding rods were distributed just outside the soil. With a new $log(C/Y)$ versus $log(E)$ graph, we obtained for our soil sample $b \approx -0.77$. For b_{situ}, we took the average of this value [1] and b_0: $(-1.12 + (-0.77))/2 \approx -0.95$. Thus, the equation that relates the count rate to the activity of isotopes in the soil is:

$$C = AY(0.0023)\left(\frac{E_\gamma}{1461 \text{ keV}}\right)^{-0.95}, \tag{2}$$

We note that there are two small optional corrections to this equation that the students can consider. If the density of the KCl sample is different from that of the soil sample, there will be a correction to ϵ_{1461}. If the density of the NaCl sample is different from that of the soil sample, there will be a correction to the ambient background. We discuss these modifications, which can change the final results for the activity of the soil by as much as 20 %, in the Appendix.

If there is not enough time to have the students determine the exponent b in situ, they can be given its value, which for our setup is -0.95. In this case, the students need only to determine ϵ_{1461} from their KCl measurement.

Table 2: Results from a student experiment for soil taken from the Bavarian forest. The soil sample and NaCl sample were each measured for 20 hours. The yields assume secular equilibrium and no radon loss.

Isotope	E_γ KeV	Yield	Soil Sample Counts	NaCl Sample Counts	Activity (Bq/Kg)
^{40}K	1461	0.1069	120000	62500	570
^{214}Bi (^{238}U series)	1764	0.153	5500	3880	14.2
^{208}Tl (^{232}Th series)	2614	0.359	13500	8000	29.5
^{137}Cs (Chernobyl)	662	0.85	58200	0	30.8

Using Eq. 2, the students determine the activities of the radioactive isotopes in soils from the count rates. Four isotopes can be detected: ^{40}K, ^{214}Bi from the ^{238}U decay series, ^{208}Tl from the ^{232}Th decay series, and sometimes ^{137}Cs from nuclear fallout. In Table 2 we list the data from a recent student measurement. Our measured values are consistent with other measurements of radiation in soils from eastern Europe [10, 11].

This experiment draws particular interest from students who grew up in Bavaria, where fallout from Chernobyl was higher than at other places in Germany. We show in Fig. 6 the region in the spectrum near 662 keV, the energy of the gamma released in the decay of ^{137}Cs. The peak at 662 keV is clearly seen. In this sample, which had the largest ^{137}Cs peak of last years student data, the activity of ^{137}Cs was measured to be around 110 Bq/kg. Although relatively large after one half-life, the ^{137}Cs activity was never larger than the naturally occuring ^{40}K activity in the soil.

5 Acknowledgments

The authors would like to thank Florian Federmann for the 3D-printing of the containers and the students in our physics laboratory who collected and analyzed the samples.

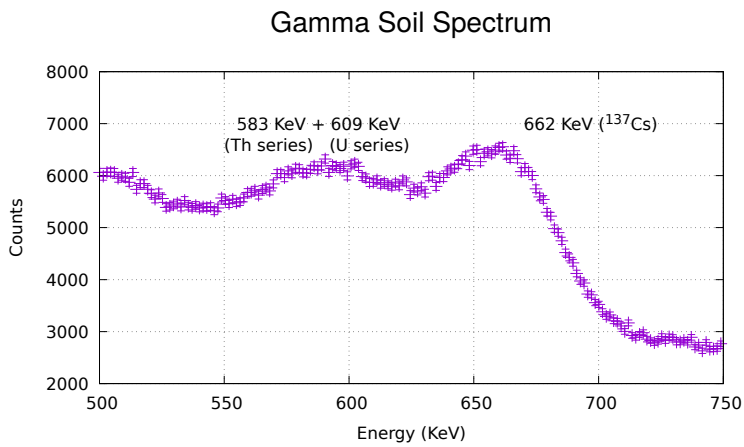

Figure 6: The 662 KeV ^{137}Cs photopeak in a 24 hour soil sample from the Bavarian forest is clearly seen. For this sample, the activity of ^{137}Cs was measured to be around 110 Bq/kg.

Appendix

We determined the efficiency constant ϵ_{1461} by recording data from a KCl sample, and the background radiation in the room was determined from a 20 hour recording of a NaCl sample. If the density of the soil, ρ_s, is the same as the density of NaCl, ρ_N, the NaCl will provide approximately the same shielding for the detector as the soil. However, if $\rho_s > \rho_N$, the soil will be a better shield, thus reducing the background radiation that reaches the detector more than the NaCl.

In a similar manner, the efficiency constant ϵ_{1461} will depend on the soil density ρ_s. If ρ_s is the same as the density of KCl, ρ_K, then the self-absorption of the 1461 keV gamma will be the same in the soil as in the KCl sample. However, if $\rho_s > \rho_K$, there will be more self-absorption in the soil, and ϵ_{1461} will be smaller for the soil sample than for the KCl sample.

Although the corrections for the difference in density of the soil sample and the calibration samples are usually small, we discuss below how one can estimate the effect of any density differences.

Background Correction:

Let $B_N(E)$ be the count rate at energy E for the $NaCl$ sample. Let $B_s(E)$ be the count rate at energy E for the soil sample if there were no

radioactive isotopes in the soil, i.e. the background radiation, which we need to subtract from the soil data. Finally, let B_0 be the count rate at energy E without any samples present.

To a good approximation, gamma radiation intensity decreases exponentially through a material according to $e^{-\alpha x}$, where x is the distance of penetration and α is the linear attenuation coefficient, which depends on the gamma energy and the type of material. As α is roughly proportional to the density of the material, the attenuation function goes as $e^{-\rho\mu x}$, where μ is the mass attenuation coefficient. Using this model, we have

$$B_s(E) = B_0(E)e^{-\rho_s \mu l} \qquad and \qquad B_N(E) = B_0(E)e^{-\rho_N \mu l}$$

,
where l is the thickness of the sample. Dividing these two equations gives

$$\begin{aligned} \frac{B_s(E)}{B_N(E)} &= e^{-\Delta\rho\mu l} \\ &or \\ B_s(E) &= B_N(E)\left(\frac{B_N(E)}{B_0(E)}\right)^{\Delta\rho/\rho_N} \end{aligned}$$

where we have used $e^{-\mu l} = (B_N(E)/B_0(E))^{1/\rho_N}$ and $\Delta\rho = \rho_s - \rho_N$. Note that if $\Delta\rho = 0$ then $B_s(E) = B_N(E)$. For the energies 1461, 1764, and 2614 keV, $B_N(E)/B_0(E)$ takes on values between 0.5 and 0.6 for our set-up. The densities of the soils we measured were around 20% larger than the NaCl density, so according to the equation above, $B_s(E) \approx B_N(E)(0.5)^{0.2} \approx 0.9B_N(E)$. That means that the soils shield the background radiation around 10% better than NaCl.

Efficiency Correction:

The efficiency constant ϵ_{1461} was measured using a sample of KCl that had the same detector-source geometry as the soil measurement. However, if the density of the soil is different than that of KCl, there will be a different amount of self-absorption in the soil compared to KCl. This will affect the value of ϵ_{1461}. To estimate the amount of self-absorption, one needs to integrate over the volume of the sample since radiation from parts of the sample close to the detector will be attenuated less than from parts further away.

The detector and the outer surface of the sample are both special cylinders, with diameter equal to height. Such a cylinder has maximum volume per surface area, similar to a sphere.

To carry out this integration, we model the detector as a sphere and the sample as a spherical shell. The diameter D of the detector and outer sample surface are chosen so that the enclosed volumes are equal to the volumes of the respective cylinders. That is $(4/3)\pi(D_{sphere}/2)^3 = \pi(D_{cyl}/2)^2 D_{cyl}$, or $D_{sphere} = (3/2)^{1/3} D_{cyl} \approx 1.145 D_{cyl}$. In addition, the sphere and the special cylinder have an overlapping volume of 86.2%, so the model should be fairly accurate.

Let D_{det} be the diameter and height of the detector, and D_{samp} be the diameter and height of the sample's outer surface. Then the corresponding detector is a sphere of radius r, where $r \approx 1.145 D_{det}/2$. The corresponding sample is a thick shell with inner radius r and outer radius $R = 1.5^{1/3} D_{samp}/2 \approx 1.145 D_{samp}/2$. The thickness of the sample l will be $l = R - r$. We perform the integral over the sample as in Ref. [1]. In our case, we will have spherical integration elements:

$$B \propto \int_0^l \frac{\pi r^2}{4\pi(x+d)^2} 4\pi(x+r)^2 e^{-\rho\mu x} dx \tag{3}$$

where B is the rate at which the gammas hit the detector. The fraction is the solid angle that the detector makes with a radiating point source. The parameter d is the distance to an effective center of the detector [1]. For our 2″ NaI detector, $d \approx 3$ cm [1]. Since the diameter of the NaI detector is $2\ in = 5.08\ cm$, d is nearly the same value as r. Setting $d = r$ in the equation above yields:

$$\begin{aligned} B &\propto \int_0^l e^{-\rho\mu x} dx \\ &\propto \frac{1}{\rho\mu l}(1 - e^{-\rho\mu l}) \end{aligned}$$

Since the efficiency is proportional to the count rate B, the ratio of the efficiency for the soil sample $\epsilon_{1461}(soil)$ to that for the KCl sample $\epsilon_{1461}(KCl)$ is given by

$$\frac{\epsilon_{1461}(soil)}{\epsilon_{1461}(KCl)} \approx \frac{\rho_K}{\rho_s} \left(\frac{1 - e^{-\rho_s \mu l}}{1 - e^{-\rho_K \mu l}} \right) \tag{4}$$

The attenuation factor $e^{-\rho_K \mu l}$ can be measured. Since the density of NaCl is nearly the same as ρ_K, we have $e^{-\rho_K \mu l} \approx B_N(1461)/B_0(1461)$. If we define $f_N \equiv B_N(1461)/B_0(1461)$, Eq. 4 becomes

$$\frac{\epsilon_{1461}(soil)}{\epsilon_{1461}(KCl)} \approx \frac{\rho_K}{\rho_s}\left(\frac{1 - f_N^{\rho_s/\rho_K}}{1 - f_N}\right) \tag{5}$$

For our setup, $f_N \approx 0.6$. For the soil sample of Table 2, $\rho_s \approx 1.2\rho_K$, which results in $\epsilon_{1461}(soil) \approx 0.95\epsilon_{1461}(KCl)$.

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