Going bananas in the radiation laboratory

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A simple setup for measuring the amount of potassium in foods is described. A 3-in. NaI detector is used to measure samples that are 3000 cm^3 in size. With moderate shielding, the potassium content can be measured down to a detection limit of a few parts per 10 000. © *1999 American Association of Physics Teachers.*

I. INTRODUCTION

A significant part of the natural background radiation that we receive on earth comes from ^{40}K. Estimates of the average annual dosage due to ^{40}K alone are around 30 mrem/yr. This is to be compared to the dosage due to all sources of natural radioactivity which, depending on geographic location, is 200–500 mrem/yr. The contribution due to ^{40}K is large because ^{40}K makes up 0.0117% of all natural potassium, which is abundant in the earth. The half-life of ^{40}K is 1.26×10^9 yr, and it decays by beta emission or electron capture. In electron capture, which occurs 11% of the time, an excited state of ^{40}Ar is formed, which in turn emits a 1.46-MeV gamma photon when it drops to the ground state. For gamma spectroscopists, this 1.46-MeV peak is an annoying source of background to be shielded against and subtracted. In the student laboratory, the 1.46-MeV peak can be measured to determine the half-life of ^{40}K. This is done by measuring the amount of radiation given off by a known amount of potassium. After correcting for detector efficiency, natural abundance, etc., the half-life of ^{40}K can be determined.

We decided to take advantage of this natural gamma source to measure the potassium content of various substances: foods and soils. In samples with a mass of around 3 kg, we were able to measure potassium levels down to a few parts in 10 000. The experiments described in this article are appropriate for upper-division undergraduate students, and we currently include a food and/or soil measurement in our upper-division radiation physics and radiation biology laboratory classes. The experiment introduces the students to natural radiation, and teaches the importance of shielding and curve-fitting techniques. The usual method of measuring mineral content in foods is by using optical spectroscopy techniques. This requires special equipment, not available at most undergraduate universities. However, gamma detectors are fairly common and offer an easy method of measuring the potassium content in various substances.[1]

We first describe the experimental setup and analysis techniques, followed by a summary of some of our results.

II. EXPERIMENTAL SETUP, PROCEDURE, AND ANALYSIS

Since there is relatively little potassium by weight, even in potassium-rich foods, the essence of the experiment is to enhance the signal over the background as much as possible. Thus one wants to use the most efficient detector possible, and a 3-in. NaI detector is the largest gamma detector available in our laboratory. For the geometry used in our experiment, the efficiency that we measured for a 1.46-MeV gamma is 0.56%.

Our goal was to measure the amount of potassium in bananas. One can estimate the sample size needed as follows: Bananas contain roughly 0.4% potassium by weight, so 1 kg of bananas contains 4 g of potassium. This amount of potassium has $(4/39\,\text{mol})*(6.02\times 10^{23})*(0.000\,117)\approx 7\times 10^{18}$ radioactive atoms of ^{40}K. Since the half-life is 1.29×10^9 yr $=6.8\times 10^{14}$ min, the activity of 1 kg of bananas is $(7\times 10^{18})*\ln(2)/(6.8\times 10^{14})\approx 7200$ decays/min. The detector efficiency for our geometry (see Fig. 1) is 0.0056, and 11% of the decays emit a gamma. This gives a counting rate of $7200*0.11*0.0056\approx 4$ counts/min. With good shielding, the ^{40}K 1.46-MeV background peak is around 8 counts/min for 3-in. NaI detectors.[2] Thus, for the signal to be equal to background, one needs around 2 kg of bananas. We note that for our samples, which had masses of around 3 kg, the sample thickness is 14 cm. Since the attenuation length of a 1.5-MeV gamma is 16 cm in water,[3] larger samples would not significantly increase the counting rate because of self-absorption.

The experimental setup is shown in Fig. 1. A large plastic container is filled with the sample and placed against the NaI detector. The sample and detector are completely shielded by lead bricks 5 cm thick to reduce the background as much as possible. The 1.46-MeV peak background, due to residual potassium in the detector and surroundings, was reduced to 9 counts/min. This value is consistent with the value referenced in Ref. 2. The detector output is fed into a multichannel analyzer which records and stores the data. After the spectrum has been taken, the area under the 1.46-MeV peak is determined by Gaussian curve fitting described in Ref. 4.

We measured food samples known to contain relatively high levels of potassium: bananas, potatoes, and prune juice. The potatoes were first softened in a microwave oven. They were then mashed by hand (including the skin) and tightly packed into the container. Care was taken to ensure there were no air pockets. The potatoes decomposed very little during the 24-h counting time. The bananas were peeled, then mashed by hand, and fit into the container. Over the 24-h counting time, they did decompose a little, and increased in volume by about 5%. A small hole was put in the top of the container to allow any gases to escape. The prune juice, 100% fruit juice, was poured into the container. A backyard soil sample was also measured.

In order to reduce the statistical and systematic errors, the data were recorded over three days as follows: First, a background with only the container was recorded for 24 h. Then the sample was recorded for 24 h. Finally, a second background was recorded for the final 24 h. The two background measurements were averaged and subtracted from the sample

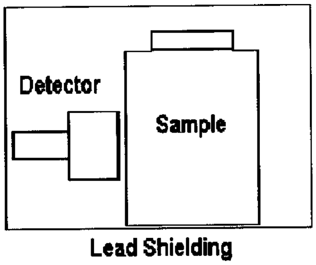

Fig. 1. Diagram of the setup for the experiment.

counts. In Fig. 2(a) we show our results for a sample of 3 kg of bananas, and that of background. In each case data were recorded for 24-h live time.

To calibrate the measurements, a known amount of potassium in the form of 70 g of crystalline KCl was mixed uniformly into each sample. In addition to calibrating with the food and soil materials, 70 g of KCl was dissolved in water and a sample of pure KCl crystals was measured as well to determine the counts/min/(g of potassium) for the 1.46-MeV gamma peak. In Table I, we list the calibration results in counts/min/(g potassium) for the different materials. All six calibration samples listed in Table I were of the same shape, of uniform density, and the same geometry with respect to the detector. Calibrating each material is necessary since self-absorption effects are, in general, dependent on the type and density of the sample. It is seen in Table I that the counts/min/(gram potassium) is approximately 1.15 and does not vary appreciably from sample to sample, except for potatoes and bananas.

III. RESULTS

Our results for the 1.46-MeV gamma peak are shown in Table II. The second row lists the background in counts/min for the 24-h period before recording the sample. The fourth row is the background for the 24-h period after recording the sample. The third row lists the area under the 1.46-MeV photopeak in counts/min for the 24-h recording period of the sample. The statistical errors are also listed in Table II, and amount to less than 1% for the food and soil samples. The fifth row is our measurement for the percent potassium by weight, and the last row lists values from other measurements.[5–7]

The photopeaks of the 1.46-MeV gamma for bananas, prune juice, and potatoes and associated backgrounds are shown in Figs. 2(a)–2(c). In all cases, the potassium from the sample is clearly seen above the background.

The two main sources of systematic error are the time dependence of the ^{40}K background, and the uncertainty in the calibration due to self-absorption. We can estimate the time dependence of the subtracted ^{40}K background from our data in Table II. Table II shows that the background varies at most 0.8 counts/min over three days, so we estimate its uncertainty to be 0.4 counts/min. Since the counts above the ^{40}K background are 8 counts/min for prune juice, 12 counts/min for bananas, and 20 counts/min for potatoes, systematic errors due to background subtraction are approximately 5%, 3%, and 2% for these foods, respectively.

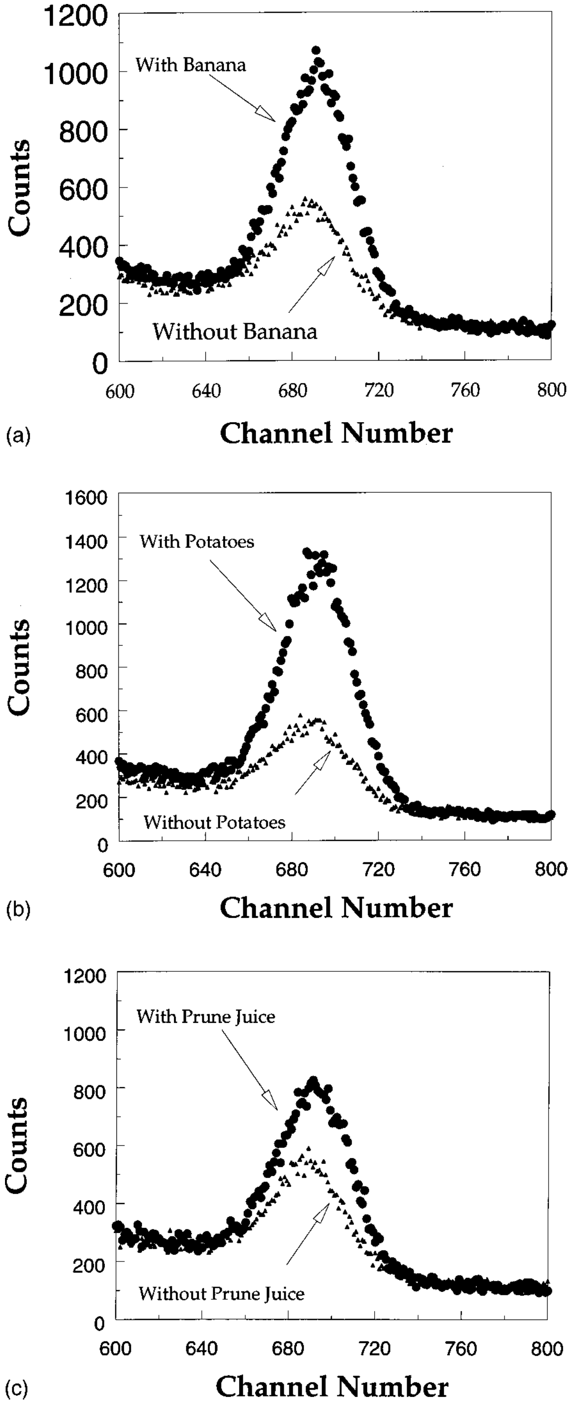

Fig. 2. The 1.46-MeV photopeaks for a collection time of 24-h for background (without sample) and sample for (a) 2975 g of bananas, (b) 3249 g of potatoes, and (c) 3102 g of prune juice.

Errors in the calibration of the counts/min/(g potassium) are due to the difficulty in obtaining good homogeneity when mixing the extra KCl for calibration. For liquid samples, KCl dissolves readily, and it is easy to obtain uniformity of the added potassium chloride. For the solid samples (e.g., bananas, potatoes, and dirt) it is more difficult to ensure that the additional KCl used for calibration is equally mixed in the sample, and hence there is a larger uncertainty. Table I shows that the counts/min/(g potassium) is similar for the two liquid samples of water and prune juice, differing only by 3%. We expect the two liquid samples to have similar values, since the main material in both samples is water. So we estimate a 2% calibration error for liquid samples. For the solid samples, the counts/min/(g of potassium) varies by roughly 15%. Self-absorption effects need not be the same

Table I. The measured counts/min/(g potassium) for the 1.46-MeV gamma emitted from ^{40}K are listed for the samples used. The same detector geometry was used in all cases, and all the samples were of uniform density.

Material	Density (g/cm^3)	Counts/min/(g potassium)
Water	1.00	1.16
KCl (salt crystals)	1.19	1.15
Prune juice	1.18	1.13
Potatoes (microwaved)	1.24	1.02
Bananas	1.14	1.02
Dirt	1.25	1.17

for the three solid food samples and the pure KCl sample, since the density and composition is different for the different materials. Our best estimate for the calibration error is 8%, half the range, for these solid samples.

We can estimate the total systematic error by combining the calibration and background uncertainties. Simply adding the two errors gives an 8% systematic error for the liquid and a 10% error for the solid foods. As seen in Table II, the statistical uncertainties are less than the systematic ones, and can be reduced to around 1% using 24-h counting times. All things considered, we estimate the overall uncertainty for the potassium content of the three foods to be around 10%.

The potassium levels in foods will vary depending on where they are grown and how they are processed. Comparing the last two rows in Table II, our results are close to other measurements. The highest amount of potassium by weight is in the Russet potatoes from Idaho that we measured, as seen in the large photopeak in Fig. 2(c). As a classroom laboratory experiment, we find prune juice the best food sample to use. Although it has less potassium by weight than bananas or potatoes, it does not spoil overnight and is easier to calibrate. It is also easier to handle and dispose of than bananas or potatoes.

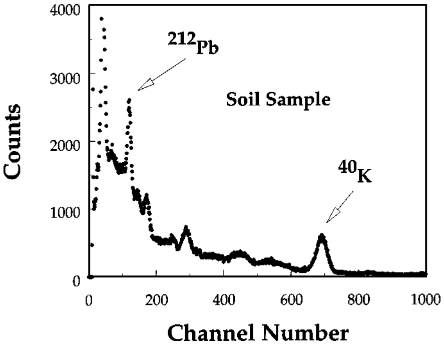

Fig. 3. Complete gamma spectra of a backyard soil sample for a collection time of 4 h. The soil sample has a mass of 3280 g and is from the city of San Dimas in the Los Angeles area.

Soils are also excellent for classroom experiments. In Fig. 3 we show a spectrum of a 4-h collection time for the soil sample listed in Table II. The higher percentage of potassium, 2% in our case, allows the student to collect meaningful soil data in a shorter time than foods. The ^{40}K background is only 1/7 of the sample's activity. In our sample, we found a peak due to the ^{232}Th decay series. In Fig. 3 the peak labeled ^{212}Pb is the 239-keV gamma from ^{212}Pb decay, which is a radionuclide in the thorium decay chain. This peak corresponds to a thorium content of roughly 200 parts per billion in this soil sample. The other peaks in the spectrum absent in the background are due to other isotopes in the ^{232}Th decay series. We are currently doing a survey of the radioisotope content in the soil in the Los Angeles area.[8]

Table II. Counts per minute for the 1.46-MeV gamma peak and percent potassium by weight for the samples measured. The counts/min were obtained for data taken over a 24-h period for a background (before), the sample measurement, and a background (after). The errors are statistical errors only.

Sample	Prune juice	Bananas	Potatoes	Soil
Mass (g)	3102	2975	3249	3280
Background (before) (counts/min)	9.6 ± 0.1	9.9 ± 0.1	10.7 ± 0.1	9.7 ± 0.1
Sample (counts/min)	17.6 ± 0.1	22.4 ± 0.2	30.2 ± 0.2	86.4 ± 0.3
Background (after) (counts/min)	9.9 ± 0.1	10.5 ± 0.1	9.9 ± 0.1	10.2 ± 0.1
Percent potassium	0.22	0.40	0.59	2.00
Other %K measurements	0.20[7]	0.39[5,6]	0.50[6] 0.45–0.54[5]	

The methods described here have practical application in environmental sampling and analysis of radioisotopes. Laboratories which regularly monitor samples use the same data analysis techniques of peak curve fitting and self-absorption corrections. To increase counting efficiency, well counters can be used, and GeLi detectors have a better energy resolution. The reader is referred to Ref. 9 for further information on the monitoring of radiation in the environment.

IV. CONCLUSION

In conclusion, we have demonstrated that it is possible using common student laboratory equipment to measure the potassium content in certain foods. In addition to teaching the students the importance of shielding, background subtraction, and curve fitting methods, the experiment is a good way to turn natural radiation into a quantitative experiment.

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[7] We used pure prune juice, whose label listed the potassium content at 0.2%.

[8] Our soil sample data are available on the web at http://www.csupomona.edu/pbsiegel/ . Spectra from our 3-in. NaI detector in ASCII format from various sites in the Los Angeles area can be downloaded.

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