Activity and Half-life of Potassium-40

Introduction

Potassium, one of the most abundant minerals on Earth, is present in most foods and is an essential element in the human body. It is also a major source of natural radiation! How much radiation does potassium produce?

Concepts

- Radioactivity
- Geiger-Müller radiation detector
- Nuclear decay equations
- Half-life

Background

Potassium occurs in nature as a mixture of three isotopes: potassium-39, potassium-40, and potassium-41. Only potassium-40, the least abundant of the three isotopes, is radioactive. The "natural abundance" of potassium-40 is extremely low, about 0.012%. (In a sample containing 100,000 atoms of potassium, 12 will be potassium-40.) This may not seem like a lot, until we consider that one gram of potassium contains 1.5×10^{22} atoms, or 1.8×10^{18} radioactive K-40 atoms.

Radioactivity is defined as the spontaneous decay or disintegration of the nucleus of an atom. Radioactive nuclei decompose by releasing *nuclear radiation* consisting of high-energy particles or photons. There are three pathways for the radioactive decay of potassium-40 nuclei—beta emission, positron emission, and electron capture. The *nuclear decay equations* for these processes are shown below (Equations 1–3). Notice that all three processes give rise to a new element, either calcium or argon.

Beta emission $${}^{40}_{19}\mathrm{K} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{40}_{20}\mathrm{Ca}$$ *Equation 1*

Positron emission $${}^{40}_{19}\mathrm{K} \rightarrow {}^{0}_{+1}\mathrm{e} + {}^{40}_{18}\mathrm{Ar}$$ *Equation 2*

Electron capture $${}^{40}_{19}\mathrm{K} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{40}_{18}\mathrm{Ar} + {}^{0}_{0}\gamma$$ *Equation 3*

The amount of radiation released by a radioactive material depends on its rate of decay. Potassium-40 is considered a very long-lived radioisotope—it takes an extremely long time for decay to occur. The rate at which a radioisotope decays is most conveniently described by the half-life ($t_{1/2}$), which is defined as the time required for one-half of the atoms of a radioisotope to emit radiation and decay to products. For potassium-40, the half-life is 1.28×10^9 years.

The relationship between the half-life of a radioactive isotope and its *rate of decay* (R) is shown in Equation 4, where N_o is equal to the number of atoms of the radioisotope initially present in the sample. The rate of decay is typically expressed as the number of disintegrations per second or, more simply, "counts per second."

$$R = (0.693/t_{1/2})\, N_o$$ *Equation 4*

The term "counts per second" comes from the name of the instrument that is most commonly used to measure nuclear radiation, that is, a Geiger counter (formally known as a Geiger-Müller radiation detector). A Geiger counter contains a sealed tube filled with argon gas. The tube is connected to a power supply and has a central wire electrode. Nuclear radiation is *ionizing radiation*—it is capable of knocking out electrons from atoms in its path. When a high-energy radiation particle or photon penetrates the detector window, the gas inside the tube becomes ionized and a current flows. The bursts of current—the number of counts—may be amplified to produce audible clicks, and they may also be recorded electronically if the radiation detector is connected to a computer.

The purpose of this experiment is to measure the radioactivity of potassium chloride and determine the half-life of potassium-40. Because of the low abundance of this isotope and its extremely long half-life, the amount of radiation emitted by a sample of KCl will be only about 2–3 times greater than the background radiation. Thus, both the background radiation and the radiation emitted from the potassium chloride sample must be measured over at least 10 minutes to obtain reliable data. The actual rate of decay of a known mass of KCl (R_{actual}) will be obtained by subtracting the background rate (R_{back}) from the measured rate of the KCl sample (R_{KCl}), and mutliplying the result by 5 (Equation 5).

$$R_{actual} = 5 \times (R_{KCl} - R_{back}) \qquad \textit{Equation 5}$$

The factor of five in this equation corrects for the efficiency of the radiation detector. On average, only about 20% of the radiation released by a sample will be "counted" by the detector. Because radiation is given off in all directions, some of the radiation will not enter the detector. Also, some of the radiation will be absorbed by the sample or by air molecules before reaching the detector. Finally, not all of the radiation that enters the detector will cause ionization.

Materials

- Potassium chloride, KCl, 2 g
- Balance, centigram
- Clamp
- Computer or calculator for data collection
- Computer interface system
- Data collection software
- Geiger-Müller radiation detector
- Metric ruler
- Spatula
- Support stand
- Watch glass or small plastic cap

Safety Precautions

The materials in this experiment are considered nonhazardous. Please observe all normal laboratory safety guidelines. It is good practice to wear chemical splash goggles whenever working with heat, chemicals or glassware. Review current Safety Data Sheets for additional information.

Procedure

1. *(Optional)* Record the efficiency of the radiation detector. If not specified, assume it is 20%.
2. Connect the interface system to a computer or calculator and then plug the Geiger-Müller radiation detector into the interface.
3. Start the data collection program and open an experiment file for the radiation detector. *Note:* Select the sensor as needed by the program or the experiment file.
4. Set a data collection interval of 900 seconds for the collection time and a sampling rate or "count interval" of 10 seconds/sample (0.1 samples/second).
5. *(Optional)* On the y-axis of the graph, set the highest value of radiation (counts) to 10.
6. Set up the radiation detector for data collection. Clamp the detector vertically to a ring stand so that the detector is one centimeter above the bench, as shown in Figure 1. Place an *empty* watch glass or bottle cap directly under the detector window.
7. Select the appropriate setting to begin "counting" the background radiation.
8. Wait 900 seconds to complete data collection. Record the total number of counts and the collection time for the background radiation. Save the experiment file as desired.
9. Remove the watch glass or plastic cap from under the radiation detector.
10. Using a 0.01-g precision balance, weigh out approximately 2 g of potassium chloride into the watch glass. Record the precise mass of potassium chloride.

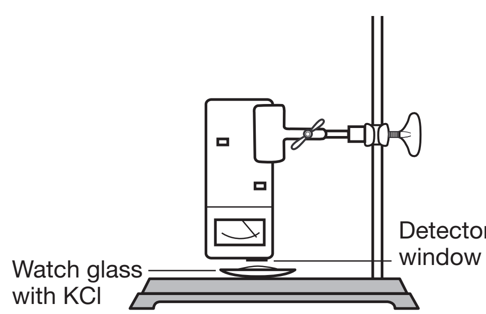

Figure 1.

11. Carefully slide the watch glass containing the potassium chloride under the detector window. Move the detector window as close to the solid as possible.
12. If necessary, open a new experiment file in the data collection program and reset the data collection interval to 900 seconds and the count interval to 10 seconds/sample.
13. Count the radiation emitted by the potassium chloride sample.
14. Wait 900 seconds to complete the data collection interval. Record the total number of counts and the collection time.

Disposal

Please consult your current *Flinn Scientific Catalog/Reference Manual* for general guidelines and specific procedures, and review all federal, state and local regulations that may apply, before proceeding. Potassium chloride may be packaged for landfill according to Flinn Suggested Disposal Method #26a.

Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

Unifying Concepts and Processes: Grades K–12
Systems, order, and organization
Evidence, models, and explanation
Constancy, change, and measurement

Content Standards: Grades 9–12
Content Standard B: Physical Science, structure of atoms, structure and properties of matter
Content Standard E: Science and Technology
Content Standard F: Science in Personal and Social Perspectives, natural and human-induced hazards

Tips

- Various types of radiation detectors, computer or calculator interface systems, and data collection software may be used to collect radiation data. Please review the instruction manual for your instrument and modify the procedure as needed for your specific instrument or software.
- Due to the low radioactivity of potassium chloride, and the low efficiency of the detector, large errors for the half-life value for potassium-40 are common.
- The detector window in a typical radiation monitor may be quite small, about 2 cm by 2 cm. (In contrast, most old fashioned analog Geiger counters had circular probes that were about 6 cm in diameter.) To maximize the efficiency of the radiation detector, adjust the sample geometry to resemble that of the detector window, i.e., the area of the sample should be about 4 cm^2. Also, place the sample as close to the detector window as possible. (Radiation intensity falls off as the distance squared from the detector.) We found that using about 2 g of KCl and placing it 1 cm from the detector gave the best results. Larger sample sizes (up to about 10 g of KCl) gave larger decay rates relative to the background radiation, as expected, but the error in the half-life calculations was typically greater. Most of the radiation was apparently absorbed by the sample.

Sample Data *(Student data will vary.)*

Mass of KCl (g)	*2.00 g**	
	Counts	**Time Interval**
Background Radiation	*155*	*900 sec*
Potassium Chloride Radiation*	*317*	*900 sec*

*Sample was placed in a 2.5-cm diameter bottle cap with a 0.7-cm high lip. Detector window 2.5 cm × 2.5 cm.

Answers to Worksheet Questions *(Student answers will vary.)*

1. $$R_{back} = \frac{155 \text{ counts}}{900 \text{ sec}} = 0.172 \text{ disintegrations/sec}$$

$$R_{KCl} = \frac{317 \text{ counts}}{900 \text{ sec}} = 0.352 \text{ disintegrations/sec}$$

2. $$R_{actual} = 5 \times (R_{KCl} - R_{back})$$

$$R_{actual} = 5 \times (0.352 - 0.172) \text{ disintegrations/sec}$$

$R_{actual} = 0.900$ *disintegrations/sec*

3. $\dfrac{2.00 \text{ g KCl}}{74.56 \text{ g/mole}} = 0.0268 \text{ moles KCl}$

$$0.0268 \text{ moles KCl} \times \frac{1 \text{ mole K}}{1 \text{ mole KCl}} \times \frac{6.02 \times 10^{23} \text{ atoms}}{\text{mole}} = 1.61 \times 10^{22} \text{ K atoms}$$

$$N_0 = 1.61 \times 10^{22} \text{ K atoms} \times \frac{0.00012 \text{ K-40 atoms}}{1 \text{ K atom}} = 1.94 \times 10^{18} \text{ K-40 atoms}$$

4. $Rate = \dfrac{0.693}{t_{1/2}} \times N_0 \text{ or } t_{1/2} = \dfrac{0.693}{Rate} \times N_0$

$$t_{1/2} = \frac{0.693}{0.900 \text{ dis/sec}} \times (1.94 \times 10^{18} \text{ K-40 atoms})$$

$$t_{1/2} = 1.49 \times 10_{18} \text{ seconds}$$

$$t_{1/2} = 1.49 \times 10_{18} \text{ sec} \times \frac{1 \text{ min}}{60 \text{ sec}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{1 \text{ day}}{24 \text{ hrs}} \times \frac{1 \text{ yr}}{365 \text{ days}} = 4.7 \times 10^{10} \text{ years}$$

5. *The main sources of experimental error are:*

   a. *The efficiency of the detector.*

   the efficiency of the detector is better than stated, the actual cps of K-40 will be lower than that calculated.

   If the calculated decay rate for K-40 is too high, the resultant calculation for $t_{1/2}$ becomes too low. The calculated value of $t_{1/2}$ becomes too high when the efficiency is underestimated.

   b. *Low activity of K-40.*

   The low count rate for K-40 makes the difference from the background count rate imprecise, even at large count times.

   c. *Self-absorption by the sample.*

   Radiation could be absorbed by atoms in the sample before the radiation can reach the detector. This would yield a count rate that is too low for the mass of KCl used. Since the half-life, $t_{1/2}$, is equal to:

$$t_{1/2} = \frac{0.693}{R} N_0$$

   when R is too low, $t_{1/2}$ is too great.

6. $N_0 = 0.500 \text{ g K} \times \dfrac{1 \text{ mole K}}{39.10 \text{ g K}} \times \dfrac{0.00012 \text{ g K-40}}{1 \text{ g K}} \times \dfrac{6.023 \times 10^{23} \text{ atoms}}{1 \text{ mole}} = 9.2 \times 10^{17} \text{ atoms K-40}$

$$R = \frac{0.693}{t_{1/2}} N_0$$

$$t_{1/2} = 1.28 \times 10^{9} \text{ yrs} \times \frac{365 \text{ days}}{1 \text{ yr}} \times \frac{24 \text{ hrs}}{1 \text{ day}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \frac{60 \text{ sec}}{1 \text{ min}} = 4.04 \times 10^{16} \text{ sec}$$

$$R(cps) = \frac{0.693}{4.04 \times 10^{16} \text{ sec}} \times 9.2 \times 10^{17} \text{ atoms K-40} = 16 \text{ cps}$$

$$R(cps) = 16 \text{ cps} \times \frac{1 \text{ Ci}}{3.7 \times 1010 \text{ cps}} \times \frac{1 \text{ pCi}}{1 \times 10^{-12} \text{ Ci}} = 4.3 \times 10^{2} \text{ pCi}$$

Materials for *Natural Radiation—Activity and Half-life of Potassium-40* is available from Flinn Scientific, Inc.

Catalog No.	Description
P0183	Potassium chloride, 100 g

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.

Name: ___________________________

Natural Radiation Worksheet

Data Table

Mass of KCl (g)		
	Counts	Time Interval
Background Radiation		
Potassium Chloride Radiation*		

*Sample was placed in a 2.5-cm diameter bottle cap with a 0.7-cm high lip. Detector window 2.5 cm × 2.5 cm.

Questions

1. For both the background radiation and the sample radiation, divide the number of "counts" by the time in seconds to obtain the rate of decay, R_{back} and R_{KCl}, respectively, in units of disintegrations per second.

2. Use Equation 5 in the *Background* section to determine the actual rate of decay (R_{actual}) of the potassium chloride sample.

3. Use the molar mass of potassium chloride and Avogadro's number to calculate the number of radioactive K-40 nuclei (N_o) in the KCl sample.

4. Use Equation 4 in the *Background* section, and the answers obtained above for *Post-Lab Questions* #2 and 3, to calculate the half-life ($t_{1/2}$) for potassium-40.

5. List three sources of experimental error that might account for errors in the half-life determination.

6. *(Optional)* An average banana contains about 500 mg of potassium. How much radiation do we ingest when a banana is eaten? Calculate the activity in units of picocuries (pCi), where 1 pCi = 1×10^{-12} Ci, and 1 Ci = 3.7×10^{10} disintegrations/second.