Radioactive Half-life of Potassium-40

Prepared by Paul C. Smithson, Berea College, based on Postma et al., 2004

To measure and count radioactive decay events in a sample of pure potassium chloride, and determine the half-life of radioactive K-40, which occurs at around 0.01% abundance in natural samples of potassium compounds. Students will learn the basic radioactive decay events, methods for calculating half-lives, and some applications of half-life measurements in rocks and minerals.

In this lab we will determine the half-life of potassium-40, a radioactive isotope of potassium (K) that occurs naturally at an abundance of about 0.0118%. The sample we will use is ordinary potassium chloride salt, KCl, which is not classified as a radioactive substance, and is perfectly safe to handle without special precautions. In fact, you may have seen a product in the grocery store sold under the name “Lite Salt”, which contains a mixture of KCl and ordinary table salt. Even so, there are enough disintegrations of K-40 that we can easily measure and count the rate of radioactive decay using a relatively simple radiation monitor.

One of the radioactive decay products of K-40 is Argon-40, and is of particular interest to geochemists because of its utility in determining the age of potassium-bearing rocks, and therefore allowing us to make estimates of the age of the earth. More on this topic later.
Natural Radioactivity
We are used to thinking of radioactivity in terms of nuclear power plants or nuclear weapons, both relatively recent and human-made phenomena. In fact, however, there are many natural sources of radioactivity, and most of our exposure to radioactivity is due to these natural sources (Figure ##-1, after Postma et al., 2004).

Figure ##-1. Sources of human exposure to radioactivity.

There are several common types of radioactive decay, producing various particles or rays, as detailed in Table ##-1 below:

Table ##-1. Summary of common types of radiation

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>Alpha particle (Helium nucleus)</th>
<th>Beta particle (electron)</th>
<th>Positron</th>
<th>Gamma ray (photon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>$^4_2 \alpha$ or $^4_2$He</td>
<td>$^0_{-1} \beta$ or $^0_{-1}e$</td>
<td>$^0_{+1} \beta$ or $^0_{+1}e$</td>
<td>$^\gamma$</td>
</tr>
<tr>
<td>Mass (amu)</td>
<td>4</td>
<td>1/2000</td>
<td>1/2000</td>
<td>0</td>
</tr>
<tr>
<td>Charge</td>
<td>+2</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
</tr>
</tbody>
</table>

Radioactive half-life
Any radioactive nucleus, known as the parent nucleus, undergoes one or more decay reactions, producing one or a series of products known as daughter nuclei. Unlike in normal chemical reactions, in which the identity of a given element is unchanged, in radioactive processes the daughter nuclei are usually different elements.

Each step in any decay sequence proceeds at a characteristic rate particular to that isotope, and is always the same for any sample of that isotope, within statistical

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uncertainty. This constant rate at which a given isotope decays is described by the decay constant $k$, with units of inverse time (1/t or $t^{-1}$).

A related concept is that of radioactive half-life, represented by the symbol $t_{1/2}$. The half-life represents the average time an atom will survive in its original state. If you start with a pure sample of an unstable element, after one half-life has elapsed, half of that sample will have decayed and half will remain. After one more half life, one-fourth of the original sample remains (i.e. half of the remaining half). After one more half-life, one-eighth remains (half of one-fourth), and so on. A graph of the decay curve looks like the following (Figure ##-2). The shape is always the same, only the time units change.

**Figure ##-2.** Generalized form of radioactive decay curve.

![Radioactive decay curve](image)

All radioactive decay processes occur according to what is known as a first-order rate process, in which the number of disintegrations in a given time is proportional to the number of particles ($N$) present. Putting this in words:

*Number of decay events per unit time = Decay rate constant $\times$ Number of radioactive atoms.*

Now in symbols:

$$- \frac{dN}{dt} = k \times N \quad \text{Equation ##-1}$$

The minus sign refers to the fact that $N$ is decreasing with time as radioactive decay occurs.

Next (trust me on this one), we integrate the above expression over a given time $t$, and find that the fraction of parent nuclei remaining at time $t$ is given by:

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\[
\ln \left( \frac{N_t}{N_0} \right) = -kt \quad \text{or} \quad \frac{N_t}{N_0} = e^{-kt}
\]

where \( N_0 \) is the amount you started with at time zero and \( N_t \) is the amount remaining at time \( t \). In the above expressions, \( \ln \) is known as the natural logarithm, and \( e \) is the base of the natural logarithm. We usually shorten this to simply natural log. Like I say, trust me, we’ll go over this in class, and I’ll show you how to use your calculators and the Excel spreadsheet program to do all the number-crunching.

We can figure out the decay constant \( k \) by measuring the number of disintegrations in a sample of the isotope we’re interested in. Finally, since we are particularly interested in determining the half-life of our decaying species, we will use our measured \( k \) value to find \( t_{1/2} \).

Here’s how we do this calculation: At an elapsed time of one half-life, half of our original radioactive nuclei remain, so \( \frac{N_t}{N_0} = \frac{1}{2} \). The natural log of \( \frac{1}{2} = -0.693 \), so we finally come up with the following:

\[
t_{1/2} = \frac{0.693}{k}
\]

**Clocks in the Rocks—radioactive dating of geological samples**

I said we are interested in figuring out the half-life of K-40. Why should we even care? It turns out that K-40 is a particularly useful isotope used by geochemists to figure out the ages of rocks, which in turn allows them to estimate the age of the earth and (from meteorite samples) the age of the solar system.

Radioactive half-lives range from seconds or less up to billions of years, according to the particular isotope in question. Of particular interest to geochemists are the decay processes that have long half-lives, which are thus useful in determining the ages of geological samples. **Table ##-2** lists the radioactive decay processes that have proven particularly useful in radioactive dating for geologic processes.
Radioactive Half-life of Potassium-40

**Table ##-2.** Commonly used isotopes for determining the age of geological samples

<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Stable Daughter Product</th>
<th>Currently Accepted Half-Life Values</th>
<th>Minerals used for dating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion years</td>
<td>Zircon, uraninite, pitchblende</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>Lead-207</td>
<td>704 million years</td>
<td>Zircon, uraninite, pitchblende</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>48.8 billion years</td>
<td>K-micas, K-feldspars, biotite, metamorphic rock, glauconite</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.25 billion years</td>
<td>Muscovite, biotite, hornblende, volcanic rock, glauconite, K-feldspar</td>
</tr>
</tbody>
</table>

**Potassium-Argon Method**

Potassium occurs in many rock types, and is relatively abundant in nature. The argon that results from the decay of K-40 is a gas, and does not occur in the structure of rocks, but is produced within the rock by the decay of K-40. Potassium-argon dating has the additional advantage that the argon does not react chemically, so any Ar found inside a rock is almost surely the result of radioactive decay of potassium. Since the argon gas will escape if the rock is melted, the dates obtained by the method measure the time since the rock was last melted.

The radioactive transition which produces the argon is a type we haven’t mentioned yet, and is called electron capture, in which the nucleus of the atom captures an inner-shell electron, converting a proton to a neutron and reducing the atomic number by one:

\[ {}^{40}_{19}K + 0^0e \rightarrow {}^{40}_{18}Ar \]  
**Equation ##-4**

Two other decay processes also occur in K-40, the first being positron emission, which also produces argon:

\[ {}^{40}_{19}K \rightarrow {}^{40}_{18}Ar + 0^0e \]  
**Equation ##-5**

and the final one (actually representing some 88% of the total radioactivity) being normal beta decay, forming stable calcium-40:

\[ {}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + 0^\text{-}1e \].  
**Equation ##-6**

As noted earlier, radioactive K-40 occurs in nature at a relative abundance of 0.0118%. This seems like very little, but it produces a sufficient number of

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disintegrations that we can easily measure the decay of K-40 in our pure KCl sample, using a fairly simple and inexpensive Geiger counter. From our radioactive decay count data, along with some necessary if somewhat tedious data manipulations, we will then calculate an estimate of the half-life of K-40.

First of all, a caution: Our homemade sample holder for counting K-40 decay has a “window” that is made of nothing but Saran Wrap. Please be careful in handling your sample holder to avoid tearing the “window” and damaging the radiation monitor. Your instructor will demonstrate how to fabricate the sample holder.

1. **Counting the background radiation**

   Radiation is all around us, and creates a low level of background counts. We have to measure the background counts and subtract that value from our K-40 counts to get the actual net counts of K-40 decay events. In order to save time in the lab, we will set up one or two radiation monitors and obtain background counts during the prelab period, and all groups will then use that number for their calculations.

2. **Counting K-40 decay**

   Weigh out 0.70 ± 0.01 g of KCl and transfer the sample quantitatively to the sample holder. Spread the KCl evenly over the entire bottom of the sample holder. Count decay events for 10 1-minute periods and record the results [Data Sheet Q1] (see example data below, Table ##-3).

   Weigh out another 0.30 g KCl and add to the sample holder (for a total now of 1.00 g). Count for 10 1-minute periods and record the results [Data Sheet Q2].

   Add another 1.00 g KCl and repeat the counting process, record the data [Data Sheet Q3] then add a final 1.00 g KCl and repeat once more [Data Sheet Q4].

   Strong suggestion to save yourself some time: Besides the data sheet provided, take the time now to set up a data table in Excel. One or two people can do this while others are setting up for the next sample run. Once you have the table set up, enter the raw data and construct formulas for all the necessary calculations. Graphing of your results will be easy once you have completed the calculations.

3. **Data analysis**

   Assuming you took my advice during step 2 above, you will be able to complete the following calculations in a few minutes using Excel.

   a. Calculate the average counts per minute for the 10 one-minute counting periods for each mass of KCl [Online Report Sheet Q5-Q8].

   b. Subtract the average background counts per minute to get net K-40 counts per minute (net CPM) [Online Report Sheet Q9-Q12].

   c. Divide by the mass of KCl for that particular sample run to get CPM per g KCl [Online Report Sheet Q13-Q16].
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d. Take the log (normal or base-10 log, not natural log) of these values [Online Report Sheet Q17-Q20].

Refer to the example below (Table ##-3) for a convenient table setup.

<table>
<thead>
<tr>
<th>Mass of KCl (g)</th>
<th>0.7</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counts per min 1</td>
<td>138</td>
<td>156</td>
<td>187</td>
<td>186</td>
</tr>
<tr>
<td>Counts per min 2</td>
<td>135</td>
<td>164</td>
<td>184</td>
<td>178</td>
</tr>
<tr>
<td>Counts per min 3</td>
<td>151</td>
<td>144</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Counts per min 4</td>
<td>126</td>
<td>130</td>
<td>201</td>
<td>176</td>
</tr>
<tr>
<td>Counts per min 5</td>
<td>151</td>
<td>142</td>
<td>179</td>
<td>200</td>
</tr>
<tr>
<td>Counts per min 6</td>
<td>126</td>
<td>155</td>
<td>189</td>
<td>191</td>
</tr>
<tr>
<td>Counts per min 7</td>
<td>117</td>
<td>161</td>
<td>161</td>
<td>181</td>
</tr>
<tr>
<td>Counts per min 8</td>
<td>139</td>
<td>142</td>
<td>187</td>
<td>170</td>
</tr>
<tr>
<td>Counts per min 9</td>
<td>127</td>
<td>184</td>
<td>183</td>
<td>173</td>
</tr>
<tr>
<td>Counts per min 10</td>
<td>127</td>
<td>179</td>
<td>180</td>
<td>158</td>
</tr>
<tr>
<td>Average counts per min</td>
<td>133.7</td>
<td>155.7</td>
<td>180.1</td>
<td>181.3</td>
</tr>
<tr>
<td>Background counts per min</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Net counts per minute (CPM)</td>
<td>114.7</td>
<td>136.7</td>
<td>161.1</td>
<td>162.3</td>
</tr>
<tr>
<td>Net CPM per g KCl</td>
<td>163.9</td>
<td>136.7</td>
<td>80.6</td>
<td>54.1</td>
</tr>
<tr>
<td>log (CPM per g KCl)</td>
<td>2.214</td>
<td>2.136</td>
<td>1.906</td>
<td>1.733</td>
</tr>
</tbody>
</table>

The reason you had to do several sample runs with varying amounts of KCl is due to the fact that as the sample mass increases, the depth of the KCl layer in the sample holder also must of course increase. The particles emitted by decaying K-40 nuclei on the top of the heap of KCl are partly absorbed by other KCl particles lower in the heap, so counts do not increase linearly with mass of KCl, but instead begin to level off.

Make a plot of counts per minute versus mass of KCl [in Excel Sheet]. Your plot will look something like Figure ##-3 (note that I have added another X-Y pair, 0 counts at 0 g KCl):
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**Figure ##-3.** Typical plot of K-40 decay with increasing mass of KCl.

![Net CPM vs g KCl](image)

Next plot the net CPM per g KCl versus g KCl [in separate Excel Sheet]. You should now have plot similar to **Figure ##-4**.

**Figure ##-4.** Typical plot of K-40 decay counts per g KCl with increasing mass of KCl.

![Net CPM/g vs g KCl](image)

Next plot the log of (net CPM/gl) versus g KCl [in separate Excel Sheet]. You should now have a more or less linear plot (**Figure ##-5**).
Figure ##-5. Logarithmic plot of K-40 decay. Note how the log plot linearizes the function.

Continuing with the analysis, add a trendline to the graph, and choose the options so that the equation of the line is displayed [from Excel Sheet].

What is all this about? At this point, you may be wondering just what is the point. To recap so far, here is what you have done, and why:

Since radioactive decay products are partly reabsorbed by the KCl sample itself, and thus never reach the detector, we need to figure out what the counts would have been had there been no reabsorption at all, which could only happen with a layer of zero thickness. Therefore, the y-intercept of the above plot (equal to 2.3484) gives the log of the CPM per gram at zero gram, or zero thickness, of KCl. Enter the value of your y-intercept [Online Report Sheet Q21].

We’re now almost through with step 1 of the data analysis. Your y-intercept is the log of the net CPM per g at zero layer thickness. Therefore you have to take the antilog of this value to get your estimate of maximum CPM per g. To take the antilog of a number, raise 10 to the power of that number (so antilog of 2.207 = 10^{2.3612} = 229.7). The value you obtain from your data will be used in succeeding calculations, so record that result [Online Report Sheet Q22].

\[
\frac{CPM}{g} = 10^{2.3484} = 223.0 \quad \text{Equation ##-7}
\]

Next we have to introduce a fudge factor to account for inefficiencies in the detector. The basic concept is not really complex. Think about how the detector and sample are arranged. The particle or photon resulting from any given decay event may be ejected in any direction, but only those that are ejected towards the detector will be counted. These and other inefficiencies in the instrument make
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for a total counting efficiency of about 20%, according to Postma et al. (2004). In other words only about 2 in 10 events, a fraction of 0.20 of all events, actually get counted. We therefore calculate a corrected CPM per g:

\[
\frac{Corrected\ CPM}{g\ KCl} = \frac{223.0}{0.20} = 1115.2\ 
\]

Equation ##-8

Enter your result for this calculation [Online Report Sheet Q23]. The value in Equation ##-8 (rounded to 1115) is the \(-dN/dt\) in the decay rate expression we derived above (Equation ##-1), which I repeat here as a reminder of where we are:

\[
\frac{-dN}{dt} = k \times N
\]

Equation ##-1

We now have a measured value approximating the left side of the equation. We want to calculate the decay constant \(k\), so we now need to figure out \(N\), which is how many atoms of K-40 there are in 1.00 g of KCl (we assume 1 g sample since we have calculated the CPM per g KCl). First recall that K-40 comprises about 0.0118% of naturally occurring K, or a fraction of 1.18 x 10^{-4}. The formula mass of KCl is 74.55 g per mole, and there are Avogadro’s number, 6.02 x 10^{23}, atoms per mole. Put all of this together, and enter your result [Online Report Sheet Q24]:

\[
N(40\ K) = 1\ g\ KCl \times \frac{1\ mol\ KCl}{74.55\ g\ KCl} \times \frac{1\ mol\ K}{1\ mol\ KCl} \times \frac{6.02 \times 10^{23} \ \text{atom}\ K}{\text{mol}\ K} \times \frac{1.18 \times 10^{-4} \ \text{atom}\ 40\ K}{\text{atom}\ K} = 9.53 \times 10^{17} \ \text{atom}\ 40\ K
\]

Equation ##-9

Now we have everything we need to solve for \(k\) in our expression:

\[
k = \frac{Corrected\ CPM}{g\ KCl} \times \frac{1\ g\ KCl}{9.53 \times 10^{17} \ \text{atom}\ 40\ K} = \frac{1115}{9.53 \times 10^{17}} = 1.17 \times 10^{-15}\ \text{min}^{-1}
\]

Equation ##-10

Now that we finally have the decay constant \(k\), we can calculate \(t_{1/2}\):

\[
t_{1/2} = \frac{0.693}{k} = \frac{0.693}{1.17 \times 10^{-15}\ \text{min}^{-1}} = 5.92 \times 10^{14}\ \text{min} \times \frac{1\ hr}{60\ \text{min}} \times \frac{1\ day}{24\ hr} \times \frac{1\ yr}{365\ \text{day}} = 1.13 \times 10^{9}\ yr
\]

Equation ##-11

i.e. 1.13 billion years for this example data set. Enter your calculated half-life in years [Online Report Sheet Q25].
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How does your calculated half-life value compare to this one? Compare your value for the half-life to a value taken from the *Handbook of Chemistry and Physics* of $1.28 \times 10^9$ yr. In your conclusion, discuss possible reasons for the difference in your value and the literature value.

**Waste Disposal and Cleanup**

The potassium chloride can be flushed down the sink with plenty of water. Remove and discard the plastic wrap and tape. Rinse out and dry the copper sample holder. Return all materials to their proper locations.

**Lab Report:** Once you have turned in your Instructor Data Sheet, lab attendance will be entered and lab attendees will be permitted to access the online data / calculation submission part of the lab report (click on **Lab ## – Radioactive Half-life of Potassium-40**). Enter your data accurately to avoid penalty. The lab program will take you in order to each calculation. If there is an error, you will be given additional submissions (the number and penalty to be determined by your instructor) to correct your calculation.

**Post-Lab Questions:** The questions for this lab can be found at [http://www.Chem21Labs.com](http://www.Chem21Labs.com). **Do Not Wait Until The Last Minute!!!! Computer Problems and Internet Unavailability Happen, But Deadlines Will Not Be Extended!!** On the Internet, complete the Post Lab Questions at the end of Laboratory 9E. The computer program will check your answer to see if it is correct. If there is an error, you will be given additional submissions (the number and penalty to be determined by your instructor) to correct your answer.

**Late Submission:** Late submission of the lab data / calculations is permitted with the following penalties: **- 10 points** for submissions up to 1 day late, **- 20 points** for submissions up to 2 days late.

**References**


Gugliotta, G. 2003. Scientists confirm ancient date of Jerusalem conduit: Siloam Tunnel may have been planned to offset siege. Washington Post, Thursday, September 11, 2003, pg A03.


[http://pegasus.phast.umass.edu/a100/handouts/raddat/raddat.html](http://pegasus.phast.umass.edu/a100/handouts/raddat/raddat.html)

[http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/raddat.html](http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/raddat.html)
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<table>
<thead>
<tr>
<th></th>
<th>Q1: 0.7 g KCl</th>
<th>Q2: 1.0 g KCl</th>
<th>Q3: 2.0 g KCl</th>
<th>Q4: 3.0 g KCl</th>
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<tbody>
<tr>
<td>Counts per minute 1</td>
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