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Exploring radioactivity safely with potassium carbonate

Extension activity: Determination of half-life

This activity is recommended for older students with some prior chemistry knowledge. It allows students to estimate the half-life of potassium-40 based on measured count rates and known quantities of material. It introduces concepts such as specific activity, decay constants, and long-lived isotopes.

Potassium-40 has an extraordinarily long half-life (~1.25 billion years) like some other prominent primordial nuclides (uranium, thorium). It is impossible to determine the half-life using a time series; you have to determine the activity (A) and the number of decaying atoms. With known mass fractions and Avogadro's number, students can link measured decay rates to the fundamental laws of radioactive decay.

This activity takes about 90 minutes (plus homework or a follow-up session).

Materials

- 20 g potassium carbonate
- G-M pancake detector
- Digital balance (precision ±0.1 g)
- Polystyrene Petri dishes, 30 mm in diameter
- Stopwatch

Procedure

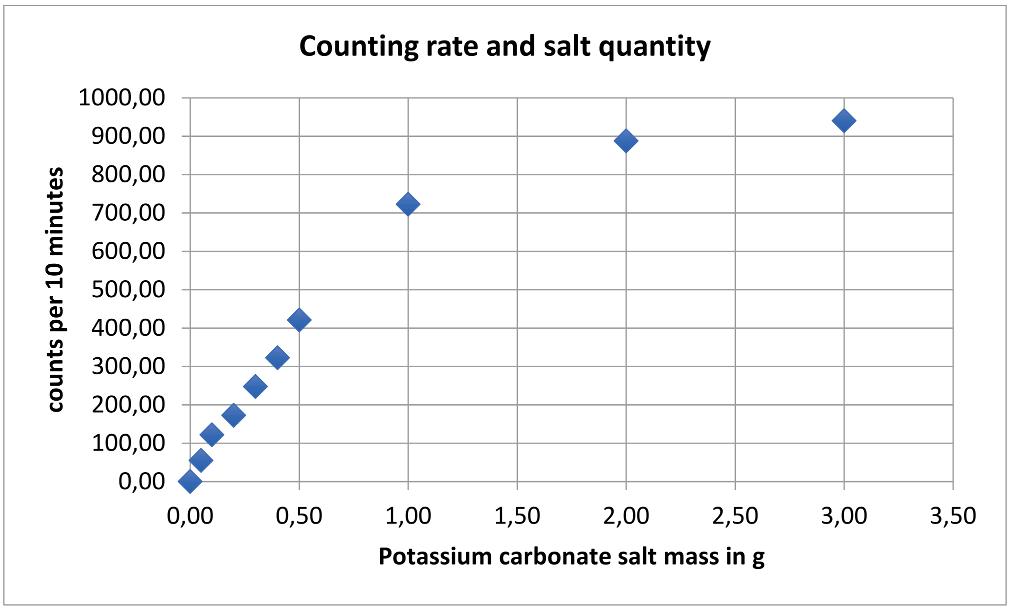
1. Prepare several samples of potassium carbonate with known masses (e.g., 0.1 g, 0.5 g, 1.5 g, 2.0 g, ... 4.0 g).
2. Fill the Petri dishes with the samples, forming homogenous thin layers.
3. Place each sample on the detector and record the count rate over a fixed time interval (e.g., 10 min).

Left: Student samples. Right: Arrangement of measurement setup
Image courtesy of the author

4. Subtract the background count rate from each measurement.
5. Plot count rate as a function of sample mass.
6. Ask students the following questions:
    - What is the relationship between sample mass and detected activity?
    - Can we determine the decay constant from our data?
    - How do we manage to calculate the self-absorption of the samples?
7. The analysis is somewhat complex, and you may have to guide the students through it step by step (see below).

Results/discussion

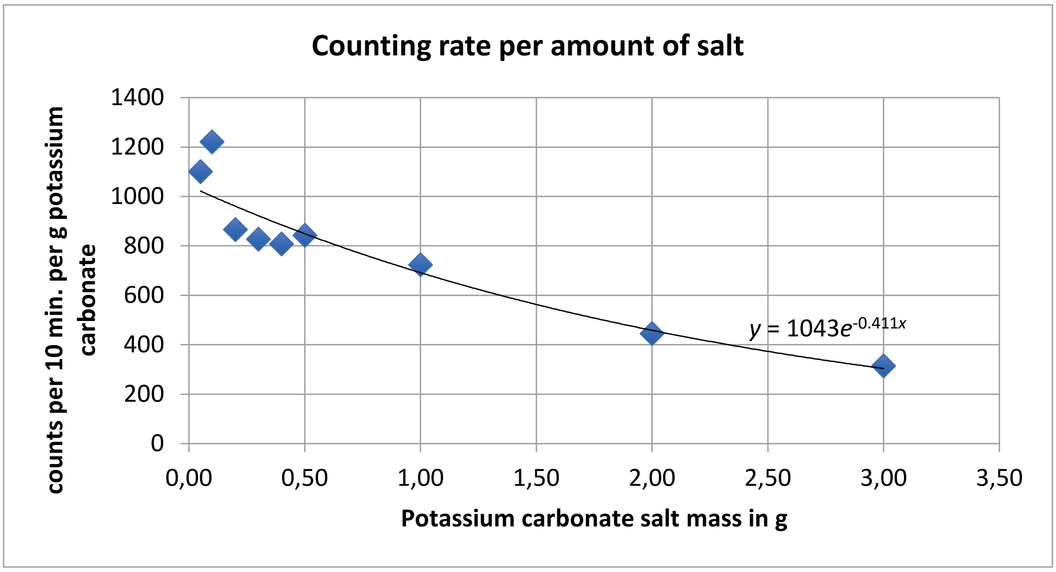
As the first step, we discuss the plot count rate as a function of sample mass.



Count rate versus mass
Image courtesy of the author

Self-absorption stops the increase of count rates beginning at approximately 3.0 g, which means a thickness of the sample of approximately 0.5 mm.

Now we produce a second plot of count rate as a function of count rate per sample mass. You just have to divide each measured value by the corresponding sample mass.



Count rate per gram
Image courtesy of the author

We can fit an exponential curve and extrapolate. The *y* intercept indicates the theoretical value per gram without self-absorption (1043 counts per gram per 10 min). This method was used by the French physicist Emile Henriot for his thesis on the radiation from potassium when it was discovered in 1912. You may have seen him in the famous picture from the Solvay congress in 1927.

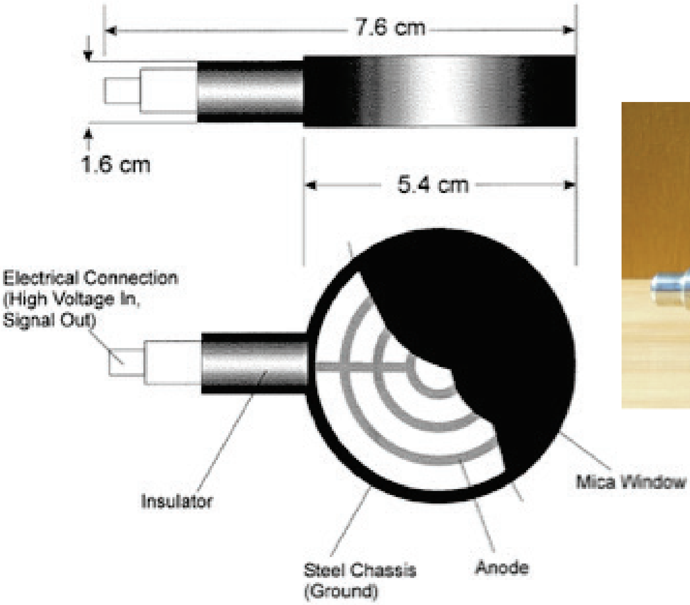
To calculate the counts per gram of potassium, you have to use the mass fraction in potassium carbonate:

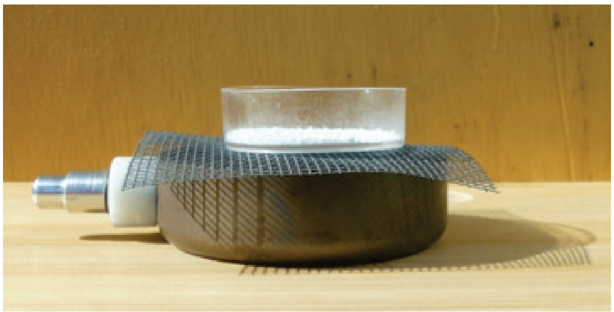
$$\frac{m_{\mathrm{K}}}{m_{\mathrm{K_2CO_2}}} = \frac{39.0983\ \mathrm{g\ mol^{-1}}}{138.205\ \mathrm{g\ mol^{-1}}} = 0.283$$

You can then calculate the count rate per gram and per second:

$$\frac{1043\,\frac{\mathrm{counts}}{10\ \mathrm{min}}}{1\ \mathrm{g\ K_2CO_3}} = \frac{1.74\ \mathrm{cps}}{1\ \mathrm{g\ K_2CO_3}} = \frac{1.74\ \mathrm{cps}}{0.283\ \mathrm{g\ K}} = 6.14\,\frac{\mathrm{cps}}{1\ \mathrm{g\ K}}$$

Don't mistake this as the activity in Bq! The beta particles are emitted randomly in every possible direction and some of them are absorbed in the base of the Petri dish. Others get into the G-M tube, but do not produce a signal. The beta response of the G-M pancake tube may be about 30%. Let the students discuss the possible efficiency of the detector.





Left: G-M pancake tube. Right: Petri dish on the G-M pancake tube
Images: Left: Taken from Ref. [1]. Right: Image courtesy of the author.

A possible result of the discussion may be a total efficiency of approximately 20%, which means you get one count from five beta decays. This corresponds to calculations and experiences of other experimenters,[1,2] and leads to the specific activity of potassium-40 of approximately 30 Bq/g.

You have to use Avogadro's number to calculate the number of potassium atoms in 1 g:

$$N_{\mathrm{K}} = \frac{6.02214076 \times 10^{23} \mathrm{mol}^{-1}}{39.0983 \text{ g mol}^{-1}} = 1.54 \times 10^{22} \text{ g}^{-1}$$

Then you need to account for the abundance of ^{40}K:

$$N_{^{40}\mathrm{K}} = 0.00012 \cdot N_{\mathrm{K}} = 1.85 \times 10^{18} \mathrm{g}^{-1}$$

Using the principal decay equation allows us to calculate the decay constant and the half-life:

$$\lambda = \frac{A}{N} \quad \text{and} \quad t_{1/2} = \frac{\ln(2)}{\lambda}$$

where A is activity in s^{-1} or Bq and N is the number of potassium-40 atoms.

But consider the two decay paths.

This means:

$$t_{1/2} = \frac{t_{1/2,\beta^-} \times t_{1/2,\mathrm{EC}}}{t_{1/2,\beta^-} + t_{1/2,\mathrm{EC}}}$$

because:

$$\lambda = \lambda_{\beta^-} + \lambda_{\mathrm{EC}}$$

$$\lambda = \frac{A_{\beta^-}}{N_{^{40}\mathrm{K}}} + \frac{A_{\mathrm{EC}}}{N_{^{40}\mathrm{K}}}$$

$$\lambda = \frac{30\ \mathrm{g^{-1}s^{-1}}}{N_{^{40}\mathrm{K}}} + \frac{3.33\ \mathrm{g^{-1}s^{-1}}}{N_{^{40}\mathrm{K}}}$$

$$\lambda = \frac{33.33\ \mathrm{g^{-1}s^{-1}}}{1.85 \times 10^{18}\ \mathrm{g^{-1}}} = 18.02 \times 10^{-18}\ \mathrm{s^{-1}}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{18.02 \times 10^{-18}\ \mathrm{s^{-1}}} = 3.85 \times 10^{16}\ \mathrm{s}$$

$$t_{1/2} = \frac{3.85 \times 10^{16}\ \mathrm{s}}{3600\frac{\mathrm{s}}{\mathrm{h}} \cdot 24\frac{\mathrm{h}}{\mathrm{d}} \cdot 365\frac{\mathrm{d}}{\mathrm{y}}} = 1.22 \times 10^{9}\mathrm{y}$$

(s=seconds, h=hours, d=days and y=years)

References

[1] Steinmeyer P (2005) G-M pancake detectors: Everything you've wanted to know. *RSO Magazine* **10**: 7–17.

[2] Radioactive half-life of potassium-40: https://www.chem21labs.com/labfiles/berea_gl07_lab.pdf