EXPERIMENT

Radioactivity: half-life of K-40

Goal

The goal of this laboratory experiment is to calculate the half-life of potassium-40 by means of the measurement of its rate of disintegration.

Materials

- ☐ A Geiger counter
- ☐ Potassium chloride
- ☐ A 100mL beaker
- ☐ A stand and a clamp

Background

Light elements have normally stable nuclei. Differently, heavier elements with atomic numbers larger than 20 tend to often have several isotopes–remember these are atoms of the element with a different number of neutrons–that have unstable nuclei. For these unstable isotopes, the forces that keep the nucleus together are not strong enough to stabilize the nuclei. An unstable nucleus is radioactive, which means that it will spontaneously emit radiation in the form of small particles. Not all radioactivity is the same and there exist different types of radiation, which we will address in the following. Table 1 reports common nuclear symbols.

alpha radiation

Alpha radiation–referred to as α–is a type of radiation that contains alpha particles. These particles are indeed helium nuclei, with 2 protons, 2 neutrons, and a (2+) positive charge. Alpha particles are often represented as α or ${}^{4}_{2}\mathrm{He}$.

beta radiation

Beta radiation–referred to as β–is a type of radiation that contains beta particles. These particles are indeed high-energy electrons with (−) negative charge. Beta particles are often represented as β or ${}^{0}_{-1}\mathrm{e}$.

gamma radiation

Gamma radiation–referred to as γ–is a type of radiation that contains high-energy photons. These particles are indeed photons with no mass or charge. Gamma particles are often represented as γ or ${}^{0}_{0}\gamma$.

protons

Protons in this chapter are often referred to as p or ${}^{1}_{1}\mathrm{H}^{+}$. These are positive charges.

positrons

Positrons are the electron antiparticle, often referred to as β^{+} or ${}^{0}_{+1}\mathrm{e}$. They do have a positive charge.

neutrons

Neutrons are nuclear particles with no charge, often referred to as n or ${}^{1}_{0}\mathrm{n}$.

Table 1 Nuclear symbols

Particle Name		Symbol	Charge	Identity	Penetrating power	Discovery
Alpha	(α)	${}^{4}_{2}\mathrm{He}$	2+	Helium nucleus	Minimal	1899
Beta	(β)	${}^{0}_{-1}\mathrm{e}$	-1	Electrons	Short	1899
Gamma	(γ)	${}^{0}_{0}\gamma$	0	Electromagnetic radiation	Deep	1900
Neutrons	(n)	${}^{1}_{0}\mathrm{n}$	0	nuclear particle	Maximal	1932
Proton	(p)	${}^{1}_{1}\mathrm{H}^{+}$	+1	nuclear particle		1919
Positrons	(β^{+})	${}^{0}_{+1}\mathrm{e}$	+1	antiparticle		1932

Isotopes–called emitters–spontaneously decompose producing new isotopes in a process called radioactive decay. In this decay, radiation is also emitted.

$$\text{Emitter} \longrightarrow \text{radiation} + \text{New isotope}$$

In the following, we will discuss the most important type of radioactive decay.

alpha decay

Some isotopes produce alpha radiation, that is, they produce α particles on its decay. A nuclear reaction that produces an α particle (${}^{4}_{2}\mathrm{He}$) is called alpha decay. In alpha decay, the emitter decreases its mass number A four units and its atomic number Z two units.

$$\text{Emitter} \longrightarrow {}^{4}_{2}\mathrm{He} + \text{New isotope}$$

beta decay

Other isotopes produce beta radiation, that is, they produce β particles on its decay. A nuclear reaction that produces a β particle (${}^{0}_{-1}\mathrm{e}$) is called beta decay. In beta decay, the emitter has the same mass number A as the product isotope. However, its atomic number Z decreases by one unit.

$$\text{Emitter} \longrightarrow {}^{0}_{-1}\mathrm{e} + \text{New isotope}$$

positron emission

Certain isotopes decay by producing a positron, that is, they produce ${}^{0}_{+1}\mathrm{e}$ particles on its decay. A nuclear reaction that produces ${}^{0}_{+1}\mathrm{e}$ is called positron emission. In a positron emission, the emitter has the same mass number A as the product isotope. However, its atomic number Z increases by one unit.

$$\text{Emitter} \longrightarrow {}^{0}_{+1}\mathrm{e} + \text{New isotope}$$

gamma decay

Some other isotopes produce gamma radiation in the form of γ particles on its decay. A nuclear reaction that produces a γ particle (${}^{0}_{0}\gamma$) is called gamma decay. In this type of decay, no new isotope is produced. Gamma emitters are normally excited, that is they have higher energy than normal; we denote this with a * symbol. Exited particles tend to lose energy to become more stable. In gamma decay, the emitter and the product isotope, both have the same mass and atomic number.

$$\text{Emitter}^{*} \longrightarrow {}^{0}_{0}\gamma + \text{Emitter}^{*}$$

Table 1 Half-life for various isotopes and chemicals

Americium-241	432.2 years	Lutetium-177	6.71 days	Hydrogen-3	12.35 years
Barium-133	10.74 years	Molybdenum-99	66 hours	Technetium-99	213,000 years
Bismuth-212	60.55 minutes	Nickel-63	96 years	Indium-111	2.83 days
Cadmium-109	464 days	Phosphorus-32	14.29 days	Technetium-99m	6.02 hours
Calcium-45	163 days	Potassium-40	1.28×10^9 years	Indium-113m	1.658 hours
Carbon-14	5730 years	Plutonium-239	24,065 years	Tin-113 115.1	days
Cesium-137	30 years	Polonium-210	138.38 days	Iodine-123	13.2 hours
Chlorine-36	301,000 years	Radium-226	1600 years	Tungsten-188	69.4 days
Chromium-51	27.704 days	Radon-222	3.8235 days	Iodine-125	60.14 days
Cobalt-57	270.9 days	Rhenium-188	16.98 hours	Uranium-235	703,800,000 years
Cobalt-58	70.8 days	Rubidium-81	4.58 hours	Iodine-129	15,700,000 years
Cobalt-60	5.271 years	Selenium-75	119.8 days	Uranium-238	4,468,000,000 years
Copper-62	9.74 minutes	Sodium-22	2.602 years	Iodine-131	8.04 days
Copper-64	12.701 hours	Sodium-24	15 hours	Xenon-127	6.41 days
Copper-67	61.86 hours	Strontium-85	64.84 days	Iron-55	2.7 years
Gallium-67	78.26 hours	Strontium-89	50.5 days	Xenon-133	5.245 days
Gold-195	183 days	Sulfur-35	87.44 days	Iron-59	44.529 days
Ondansetron	360 min	Capecitabine	2400s	Carmustine	0.25h

Radioisotopes–isotopes that decay producing radiation–are unstable and with time they eventually disappear given a more stable isotope. Some radioisotopes decay very quickly, such as the ones used in nuclear medicine to fight cancer. Other radioisotopes take longer to disappear.

The concept of half-live

The half-life of an isotope represented as $t_{1/2}$ is the time it takes for an isotope to disappear reducing the sample mass to half the initial value. For example, $t_{1/2}$ for chromium-51 is 28 days and that means that after 28 days a sample of 1 gram of the radioisotope will indeed weigh 0.5 g. Table 1 reports half-lives of numerous isotopes. Samples of radioisotopes weigh less and less with time as they decompose producing more stable isotopes. Similarly, $t_{1/2}$ for strontium-90 is 38 years which means that a one-gram sample will take 38 years to reduce its mass to 0.5g. We can use the concept of half-life to compare the speed of decomposition of different radioisotopes. For example $t_{1/2}$ for strontium-90 is 38 years whereas $t_{1/2}$ for chromium-51 is 28 years. Hence, strontium-90 will exist longer than chromium-51. The activity of an isotope is indeed its rate of the decomposition r which depends on the amount of radioactive isotope you have in the sample n,

$$r = kn$$

where k is the rate constant for the decomposition. At the same time this rate constant is related to half-life, as decomposition is a first order reaction:

$$t_{1/2} = \frac{0.693}{k}$$

Quantifying half-live

The formula that related the amount of radioisotope with $t_{1/2}$ is:

$$\boxed{N(t) = N_o \cdot 0.5^{\left(\frac{t}{t_{1/2}}\right)}} \tag{1}$$

where $N(t)$ is the amount of isotope at a given time t, N_o is the initial amount of isotope, t is the time and $t_{1/2}$ is the half-life. $N(t)$ is often referred to as the activity of the radioisotope at a given time t. At the same time, while the radioisotope disappears, a new isotope–this time more stable than the radioisotope–starts forming. The amount of product formed $F(t)$

at a given time is:

$$\boxed{F(t) = N_o \cdot \left[1 - 0.5^{\left(\frac{t}{t_{1/2}}\right)}\right]} \tag{2}$$

After several half-lives

So if the half-life is the time it takes for a radioisotope to decompose in half, what would happen after several half-lives? For example, imagine we have 20 grams of iridium-131 with a half-life of 8 days. When we prepare or hypothetically unseal the sample, we will have 20 grams of ^{131}Ir. After one half-life (8 days) we'll have 10 grams of ^{131}Ir. After two half-lives (16 days), we'll have 5 grams of ^{131}Ir. Similarly, after three half-lives (22 days), we'll have 2.5 grams.

Example

$^{131}_{53}I$ has a half-life of 8days. How many milligrams of a 50mg sample will remain after 10 days.

Answer: We will following steps to solve this problem:

1. **Step one:** list of the given variables.

2. **Step two:** use the half-life formula $N(t) = N_o \cdot 0.5^{\frac{t}{t_{1/2}}}$ to obtain the mass remaining of the radioisotope

$$N(t) = \underbrace{N_0}_{\text{50mg}} \cdot 0.5^{\frac{\overbrace{\text{t}}^{\text{10d}}}{\underbrace{t_{1/2}}_{\text{8d}}}}$$

3. **Step three:** solve for $N = 50 \cdot 0.5^{\frac{10}{8}} = 50 \cdot 0.5^{1.25} = 21 mg$. The result means that after 10 days from the 50mg sample of radioisotope, only 21mg will remain due to radioactive decay.

Procedure

Part A: Background measurement

- [ ] *Step 1:* – Obtain a Geiger counter. Turn it on and let it warm up for five minutes.

- [ ] *Step 2:* – Start the Geiger counter. Set up the measurement time to 60 seconds and the measuring voltage according to your professor's instructions. Mind to select a voltage of 900V for all measurements (Press Display/High Voltage/Up/Down until you reach 900V). Press measure (press Display until the light cursor is next to count; then press Count until the stop button lights up.) and write down the background radioactivity in counts per minute in the table below.

- [ ] *Step 3:* – Measure the background radiation by reading the meter 10 times.

- [ ] *Step 4:* – Compute the average activity and standard deviation.

Part B: Calculation of $t_{1/2}$ for a set of mass measurements

- ☐ *Step 1:* – Weight between 10 and 11 grams of KCl in a scale. Write down your measurement. Place the sample in a 100mL beaker.
- ☐ *Step 2:* – With the help of a stand, clamp the counter as close a possible to the sample but without touching the sample. Be very careful with the membrane at the end of the counter as it is very delicate and tears easily.
- ☐ *Step 3:* – Set up the measurement time to 60 seconds and the measuring voltage according to your professor's instructions. Mind to select a voltage of 900V for all measurements (Press Display/High Voltage/Up/Down until you reach 900V). Press measure (press Display until the light cursor is next to count; then press Count until the stop button lights up.) and write down the activity in counts per minute in the Results section.
- ☐ *Step 4:* – Measure radiation by reading the meter 10 times.
- ☐ *Step 5:* – Repeat Part A for a set of K masses between: 14-15g, 19-20g, and 24-25g.
- ☐ *Step 6:* – For each sample compute the average activity $\overline{A}$ in cps and the number of 40-K atoms in the sample, N.
- ☐ *Step 7:* – Plot $\overline{A}$ in cps in the vertical axis versus N in the horizontal axis.
- ☐ *Step 8:* – Compute the half-life for each mass measurement with its average.
- ☐ *Step 9:* – From the slope of your plot calculate the half-life of the isotope.
- ☐ *Step 10:* – Compare the calculated half-lives with the experimental value.

Calculations

(0) The mass of K your weighted, m.

(1) The number of 40-K atoms in you sample, n:

$$N = \frac{m \cdot N_o \cdot f}{AW} = (0) \cdot 6.02 \times 10^{23} \cdot 0.00012/39.0983$$

(2) The average activity in cpm.

(3) The average activity in cps:

$$A(cps) = (2)/60$$

(4) The standard deviation in cps.

(5) These are the activity values in cpm for the background (without K).

(6) These are the activity values in cpm for the sample.

(7) These are the activity values in cpm for the sample without the background. You can susbtract the average value and the standard deviation.

$$(6) - (5)$$

8 Calculated half-life of the isotope in years (the one measured in the experiment). In the formula below you need to use the Activity in cps.

$$t_{1/2}^{calc.} = \frac{0.693 \cdot 1}{7 \cdot 31536000}$$

9 The sum of activity times mass and mass squared

10 The average half-life

11 Half-life calculated by means of a linear regression

$$t_{1/2}^{calc.}(LR) = \frac{0.693}{31536000} \times \frac{\sum m^2}{\sum A \cdot m}$$

12 Experimental half-life of the isotope in years (the one obtained from the tables)

13 The percent error

STUDENT INFO

Name: ____________________ Date: __________

Pre-lab Questions

Radioactivity: half-life of K-40

---

1. Research the half-life of the following isotopes: (a) Chlorine-36 (b) Cadmium-109 (c) Copper-64 (d) Chromium-51 (e) Carbon-14 (f) Gold-195 (g) Calcium-45

2. Classify the following nuclear reactions as: (a) α decay (b) β decay (c) γ decay (d) positron emission (e) electron capture (i) ${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta$ (ii) ${}^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{+1}\beta^{+}$ (iii) ${}^{55}_{26}Fe + {}^{0}_{-1}\beta \longrightarrow {}^{55}_{25}Mn + X\text{–ray}$ (iv) ${}^{234}_{88}Th^{*} \longrightarrow {}^{234}_{88}Th + {}^{0}_{0}\gamma$ (v) ${}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$

3. The half-life of bromine-74 is 25 min. How much of a 100 mg sample is still active after 100 min?

4. Identify the unknown radioactive particle involved in the following nuclear equations: (a) ${}^{9}_{4}Be + {}^{A}_{Z}X \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n$ (b) ${}^{31}_{15}P + {}^{1}_{1}H \longrightarrow {}^{31}_{16}S + {}^{A}_{Z}X$ (c) ${}^{3}_{1}H + {}^{2}_{1}H \longrightarrow {}^{A}_{Z}X + {}^{1}_{0}n$ (d) ${}^{14}_{6}C \longrightarrow {}^{A}_{Z}X + {}^{0}_{-1}\beta$

5. Indicate the nuclear symbol for (a) Oxygen-18 (b) Magnesium-24 (c) Lithium-7

STUDENT INFO

Name: ____________ Date: ________

Results
EXPERIMENT

Radioactivity: half-life of K-40

0 m (K) in g=____________ 1 N (^{40}K) in atoms=____________

Part A													
Activity, A (cpm)	1	2	3	4	5	6	7	8	9	10	$\overline{A}$ (cpm) 2	$\overline{A}$ (cps) 3	s(cps) 4
Background 5													
Sample + Background 6													
Sample 7													

0 m (K) in g=____________ 1 N (^{40}K) in atoms=____________

Part B													
Activity, A (cpm)	1	2	3	4	5	6	7	8	9	10	$\overline{A}$ (cpm)	$\overline{A}$ (cps)	s(cps)
Sample + Background 6													
Sample 7													

0 m (K) in g=____________ 1 N (^{40}K) in atoms=____________

Activity, A (cpm)	1	2	3	4	5	6	7	8	9	10	$\overline{A}$ (cpm)	$\overline{A}$ (cps)	s(cps)
Sample + Background 6													
Sample 7													

0 m (K) in g=____________ 1 N (^{40}K) in atoms=____________

Activity, A (cpm)	1	2	3	4	5	6	7	8	9	10	$\overline{A}$ (cpm)	$\overline{A}$ (cps)	s(cps)
Sample + Background 6													
Sample 7													

m (g) 0	$t_{1/2}$ (s) 8	A (cpm) 2	$A \cdot m$ 0 × 2	m^2 0 × 0
		9 Sum (∑)=		

10 $\bar{t}_{1/2}^{calc.}$ (years)=________ 12 $t_{1/2}^{theory}$ (years)=________ 13 % error=________

11 $t_{1/2}^{calc.}(LR)$ (years)=________ 12 $t_{1/2}^{theory}$ (years)=________ 13 % error=________

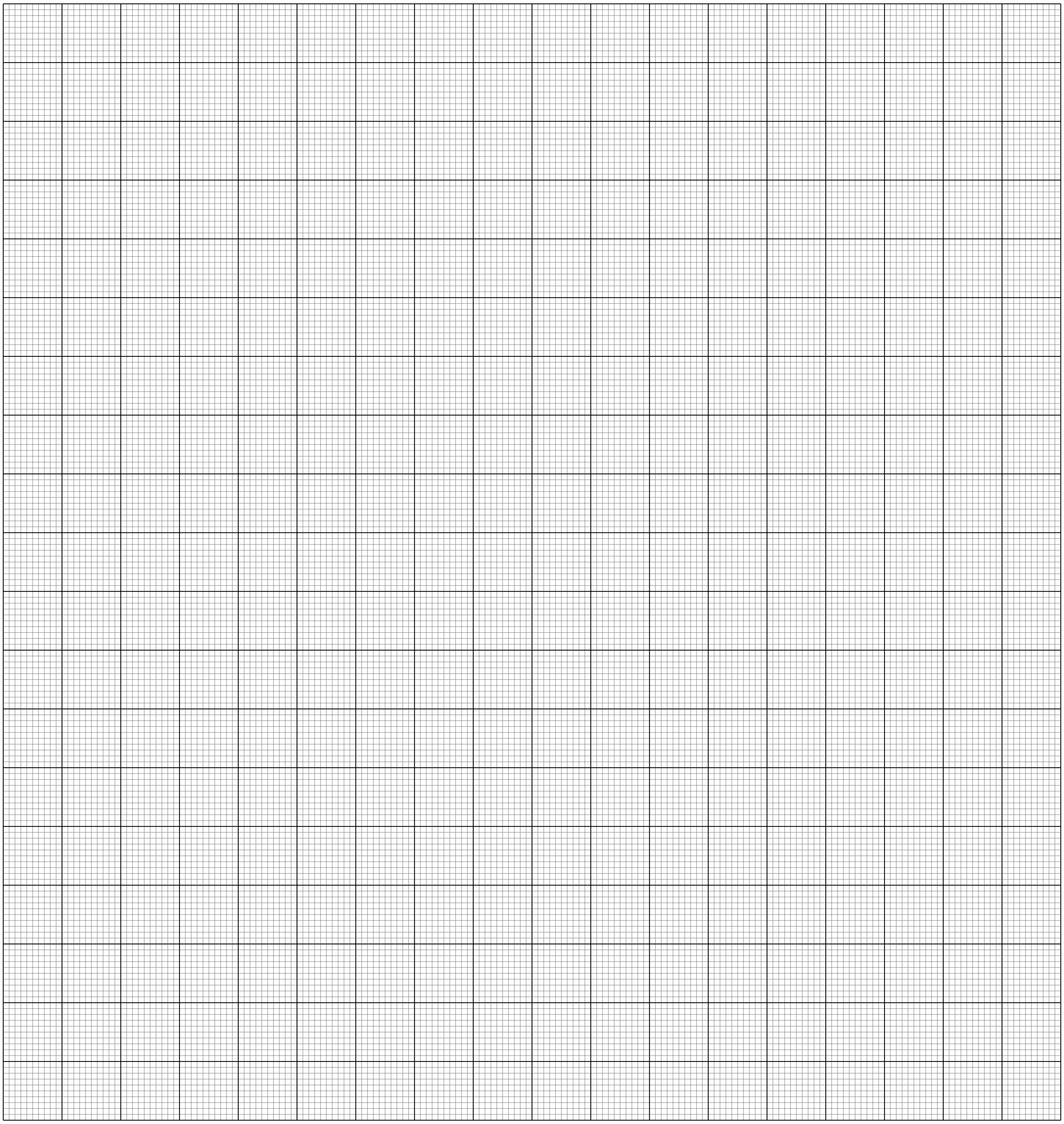

Figure 2: $\overline{A}$ cps (Y axis) vs. N (X axis)

STUDENT INFO

Name: ____________ Date: ________

Post-lab Questions

Radioactivity: half-life of K-40

---

1. Classify the following nuclear reactions as: (a) α decay (b) β decay (c) γ decay (d) positron emission (e) electron capture (i) $^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$ (ii) $^{42}_{19}K \longrightarrow {}^{42}_{20}Ca + {}^{0}_{-1}e$ (iii) $^{15}_{8}O \longrightarrow {}^{15}_{7}N + {}^{0}_{+1}e$ (iv) $^{228}_{88}Ra \longrightarrow {}^{228}_{89}Ac + {}^{0}_{-1}e$ (v) $^{13}_{6}C + {}^{1}_{1}H \longrightarrow {}^{14}_{7}N + {}^{0}_{0}\gamma$

2. Indicate the name of the following nuclear symbols: (a) $^{0}_{+1}e^{+}$ (b) $^{0}_{0}\gamma$ (c) $^{1}_{1}H$

3. Research the half-life of the following isotopes: (a) Potassium-40 (b) Cesium-137 (c) Cobalt-57 (d) Bismuth-212 (e) Gallium-67 (f) Americium-241

4. The half-life of bromine-74 is 25 min. 20mg of the isotopes remain after 10 minutes of preparing the sample. Calculate the initial mass of the bromine-74 sample.