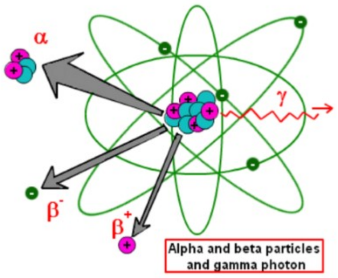
Nuclear Chemistry



Unit Vocabulary:

- Alpha particle
- Artificial transmutation
- Beta particle
- Fission
- Fusion
- Gamma radiation
- Half-life
- Radioactive tracer
- Radioisotope
- Transmutation

Unit Objectives:

Upon completion of this unit you should be able to do the following:

- Predict the stability of an isotope based on the ratio of neutrons and protons in its nucleus.
- Understand that while most nuclei are stable some are unstable and spontaneously decay emitting radiation.
- Calculate the initial amount of the fraction remaining, or the half life of a radioactive isotope, using the half life equation.
- Understand the concept of half life.
- Differentiate between the following emissions based on mass, charge, ionizing power, and penetrating power:
    - ✓ Alpha
    - ✓ Beta
    - ✓ Positron
    - ✓ Gamma
- Determine the type of decay (alpha, beta, positron, gamma) and write the nuclear equations.
- Compare and contrast fission and fusion reactions
- Distinguish between natural and artificial transformations.
- Complete nuclear equations and predict missing particles from nuclear equations.
- Understand the change in energy in a nuclear reaction.
- Be aware of the risks associated with radioactivity.
- Recognize the beneficial uses and real world application of radioactive isotopes.
    - ✓ Radioactive dating
    - ✓ Tracing chemical and biological processes
    - ✓ Industrial measurement
    - ✓ Nuclear power
    - ✓ Detection and treatment of diseases

Nuclear Chemistry - study of reactions that are caused by a CHANGE IN THE NUCLEUS of an atom (to BECOME ANOTHER ELEMENT); has nothing to do with electrons, just protons and neutrons (since these two reside in the nucleus!)

Stability of Nuclei:

- ※ **Large Atom Rule** – elements with an ATOMIC NUMBER > 83 (z > 83) are NATURALLY RADIOACTIVE due to an UNSTABLE PROTON/NEUTRON RATIO; they have no known stable isotopes so they are continually decaying

- ※ **Small Atom Rule** – elements with an ATOMIC NUMBER < 84 (z < 84) have ***at least*** one stable isotope

  Exception to "Small Atom Rule:"

  - ※ TECHNETIUM has no known stable isotopes due to an UNSTABLE PROTON/NEUTRON RATIO

Radioisotope (Table N): an UNSTABLE or RADIOACTIVE ISOTOPE of any element

Let's Try Some:

Element	Nuclear Symbol	Mass	Stable (Yes/No/?)
Calcium Ca	Ca^{37}_{20}	37	stable
Hydrogen	H^{1}_{1}	1	stable
Oxygen	O^{16}_{8}	16	stable
Oxygen	O^{14}_{8}	14	stable
Neptunium	Np^{237}_{93}	237	unstable

So what happens to a substance with an unstable nucleus?

It will naturally (spontaneously) decay to form a more stable substance/element

Transmutation: the transformation of a nucleus of one element into the nucleus of another element (by gaining, losing, or changing nucleons) < Protons
Neutrons

Transmutations

Natural: radioisotopes (unstable or radioactive isotopes) undergo spontaneous nuclear decay in order to increase stability

$${}^{238}_{92}\text{U} \rightarrow {}^{4}_{2}\text{He} + \boxed{{}^{234}_{90}\text{Th}}$$

(Radioisotope) (Decay) (New isotope)

Natural Transmutation includes the following (at Earthly conditions):

1. Alpha
2. Beta
3. Positron
4. Gamma
5. *Electron capture

Induced/Artificial: involves some kind of high energy particle being used to bombard a nucleus; can occur with stable or unstable isotopes

$${}^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow \boxed{{}^{18}_{9}\text{F}}$$

Artificial/Induced Transmutation includes the following (at Earthly conditions):

1. Nuclear bombardment (general)
2. Fission (splitting atoms)
3. Fusion (combining atoms)

Table O: Symbols Used in Nuclear Chemistry:

Types of Radiation	Source	Description/ Symbol	Mass	Hazard	Shielding Needed
Alpha Particle α	naturally occurring elements	${}^{4}_{2}He$ ${}^{4}_{2}\alpha$	4 amu	No external hazard, internal though!	Skin Paper
Beta Particle β^- or e^-	Atomic nucleus of most radioisotopes	${}^{0}_{-1}e$ ${}^{0}_{-1}\beta$	0 amu	Dangerous internally & externally	Cardboard Tin foil
Positron β^+ or e^+	Radioactive isotopes	${}^{0}_{+1}e$ ${}^{0}_{+1}\beta$	0 amu	Dangerous internally & externally	Cardboard Tin foil
Gamma Rays γ	Nearly all nuclear reactions	Electromagnetic radiation Similar to x-rays	0 amu	Very dangerous (highly penetrating)	Very heavy lead shield or suit Concrete

****Radiation can damage our cells by causing mutations in our DNA**

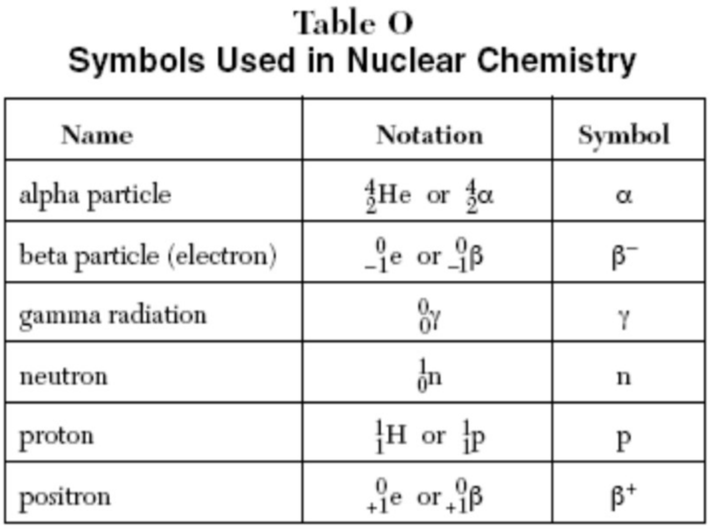
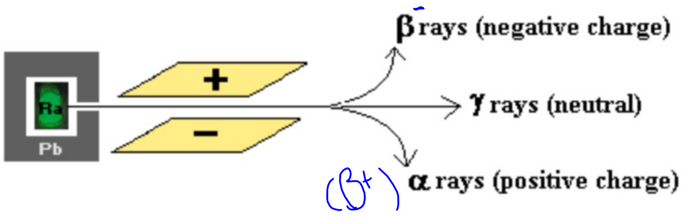


Table O
Symbols Used in Nuclear Chemistry

Name	Notation	Symbol
alpha particle	${}^{4}_{2}\text{He}$ or ${}^{4}_{2}\alpha$	α
beta particle (electron)	${}^{0}_{-1}\text{e}$ or ${}^{0}_{-1}\beta$	β^-
gamma radiation	${}^{0}_{0}\gamma$	γ
neutron	${}^{1}_{0}\text{n}$	n
proton	${}^{1}_{1}\text{H}$ or ${}^{1}_{1}\text{p}$	p
positron	${}^{0}_{+1}\text{e}$ or ${}^{0}_{+1}\beta$	β^+

Separation of Nuclear Particles by Electric/Magnetic Fields:



- Positive alpha particles attract to the negative plate (do not deflect as much as beta particles since they are heavier)

- Negative beta particles attract to the positive plate (lighter so they bend more toward plate than alpha particles)

- Neutral gamma rays have no charge so they are undeflected in the electrical field (so straight through between the two plates)

Natural Transmutation/Selected Radioisotopes (Table N):

- Table N contains a list of some of the more common radioisotopes, their half-lives, their symbols, and their names
- **NUCLIDE** = an **ISOTOPE** of a given element

1. Which of the following pairs of nuclides has the same type of radioactive decay mode?
    a. K-37 and K-42
    [✓ b. Fr-220 and Th-232]
    c. Ne-19 and P-32
    d. U-232 and U-235
2. Which of the following radioisotopes will take the longest to decay from 100 g to 50 g?
    a. Fe-53 8.51 min
    b. Pu-239 >10^4 y
    [✓ c. Th-232] × 10^{10} y
    d. N-16 7.2 s
3. Which of the radioisotopes listed below emits a decay product with a positive charge?
    [✓ a. Ra-226] → α $^{4}_{2}He$
    b. Au-198
    c. H-3
    d. Sr-90
4. Which of the radioisotopes listed below emits a decay product with the greatest mass?
    a. Co-60 β^-
    b. C-14 β^-
    c. Ca-37 β^+
    [✓ d. Fr-220] α

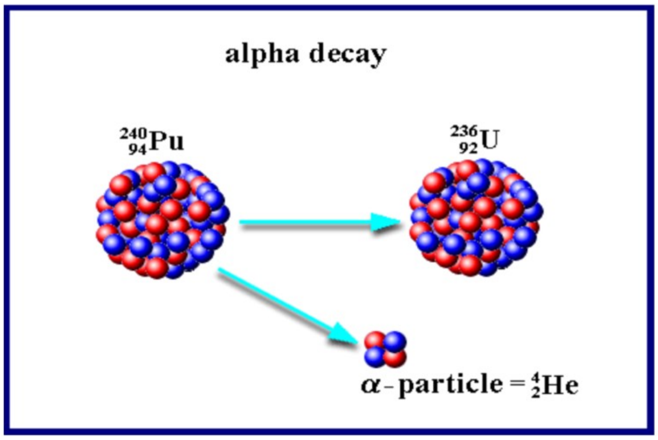
Table N
Selected Radioisotopes

Nuclide	Half-Life	Decay Mode	Nuclide Name
^{198}Au	2.69 d	β^-	gold-198
^{14}C	5730 y	β^-	carbon-14
^{37}Ca	175 ms	β^+	calcium-37
^{60}Co	5.26 y	β^-	cobalt-60
^{137}Cs	30.23 y	β^-	cesium-137
^{53}Fe	8.51 min	β^+	iron-53
^{220}Fr	27.5 s	α	francium-220
^{3}H	12.26 y	β^-	hydrogen-3
^{131}I	8.07 d	β^-	iodine-131
^{37}K	1.23 s	β^+	potassium-37
^{42}K	12.4 h	β^-	potassium-42
^{85}Kr	10.76 y	β^-	krypton-85
^{16}N	7.2 s	β^-	nitrogen-16
^{19}Ne	17.2 s	β^+	neon-19
^{32}P	14.3 d	β^-	phosphorus-32
^{239}Pu	2.44×10^4 y	α	plutonium-239
^{226}Ra	1600 y	α	radium-226
^{222}Rn	3.82 d	α	radon-222
^{90}Sr	28.1 y	β^-	strontium-90
^{99}Tc	2.13×10^5 y	β^-	technetium-99
^{232}Th	1.4×10^{10} y	α	thorium-232
^{233}U	1.62×10^5 y	α	uranium-233
^{235}U	7.1×10^8 y	α	uranium-235
^{238}U	4.51×10^9 y	α	uranium-238

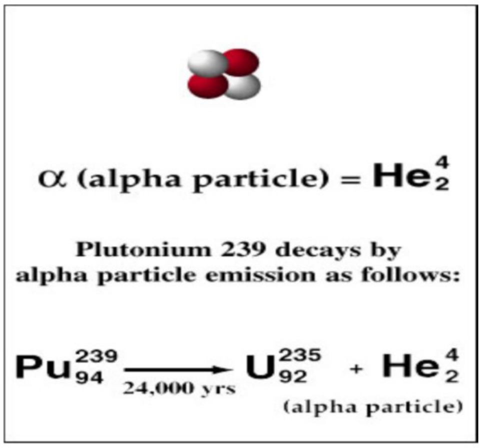
ms = milliseconds; s = seconds; min = minutes;
h = hours; d = days; y = years

Radioactive Decay: The following decays occur in nature as a result of UNSTABLE NEUTRON-TO-PROTON RATIOS.

1. **Alpha Decay:** This is a transmutation whereby an unstable nucleus emits alpha particles. ALPHA PARTICLES are PRODUCTS in the reaction and the nucleus becomes smaller with less positive charge. Alpha emission is characteristic of HEAVY NUCLEI (especially with atoms greater than 83).
    a. Example:



b. Alpha decay can be summarized as follows:
    i. Atomic number decreases by 2
    ii. # protons decreases by 2
    iii. mass decreases by 4
    iv. # neutrons decreases by 2



α (alpha particle) = He_2^4

Plutonium 239 decays by alpha particle emission as follows:

$$Pu_{94}^{239} \xrightarrow[\text{24,000 yrs}]{} U_{92}^{235} + He_2^4$$

(alpha particle)

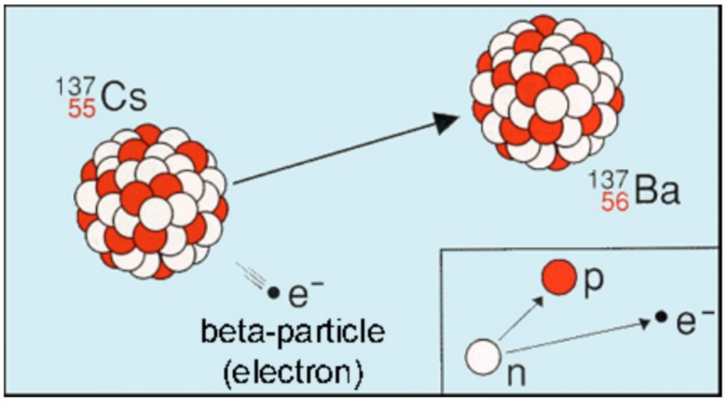
c. Complete the example problems below showing ALPHA DECAY (remember, CHARGE and MASS must be conserved!)

1) $^{220}_{87}\text{Fr} \rightarrow \boxed{^{216}_{85}\text{At}} + ^{4}_{2}\text{He}$

2) $^{222}_{86}\text{Rn} \rightarrow \boxed{^{218}_{84}\text{Po}} + \boxed{^{4}_{2}\text{He}}$

2. **<u>Beta Decay</u>:** A nucleus whereby a BETA PARTICLE is EMITTED (PRODUCED) as a result of nuclear disintegration; something said to undergo beta decay is called a "beta emitter."

a. Example:



$^{137}_{55}\text{Cs} \rightarrow ^{137}_{56}\text{Ba} + ^{0}_{-1}\text{e}$

b. Beta decay can be summarized as follows:

i. Atomic # increases by 1
ii. # protons increases by 1
iii. mass stays the same
iv. # neutrons decreases by 1

c. Complete the example problems below showing beta decay:

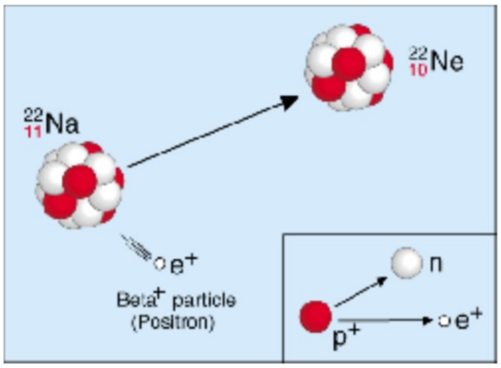
1) $^{32}_{15}\mathrm{P} \rightarrow \boxed{^{32}_{16}\mathrm{S}} + {}^{0}_{-1}\mathrm{e}$

2) $^{14}_{6}\mathrm{C} \rightarrow \boxed{^{14}_{7}\mathrm{N}} + \boxed{^{0}_{-1}\mathrm{e}}$

3) $^{214}_{82}\mathrm{Pb} \rightarrow \boxed{^{214}_{83}\mathrm{Bi}} + \boxed{^{0}_{-1}\mathrm{e}}$

3. **Positron Emission:** Occurs when a POSITRON is PRODUCED during the conversion of a proton to a neutron. β^+

a. Example:



$$^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{\underline{+1}}\mathrm{e}$$

b. Positron Emission can be summarized as follows:

i. Atomic # decreases by 1
ii. # protons decreases by 1
iii. mass stays the same
iv. # neutrons increases by 1

c. Complete the example problems showing positron emission:

1) ${}^{37}_{19}\text{K} \rightarrow \boxed{{}^{37}_{18}\text{Ar}} + {}^{0}_{+1}\text{e}$

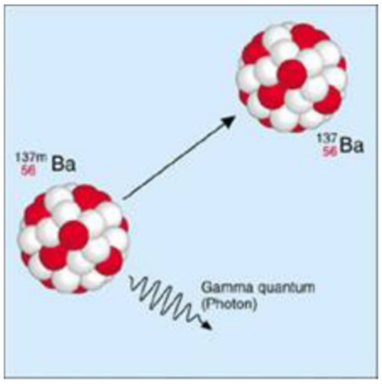
2) ${}^{81}_{37}\text{Rb} \rightarrow \boxed{{}^{81}_{36}\text{Kr}} + \boxed{{}^{0}_{+1}\text{e}}$

3) ${}^{19}_{10}\text{Ne} \rightarrow \boxed{{}^{19}_{9}\text{F}} + \boxed{{}^{0}_{+1}\text{e}}$

4. **<u>Gamma Rays</u>:** a highly penetrating type of nuclear radiation, similar to x-rays and light

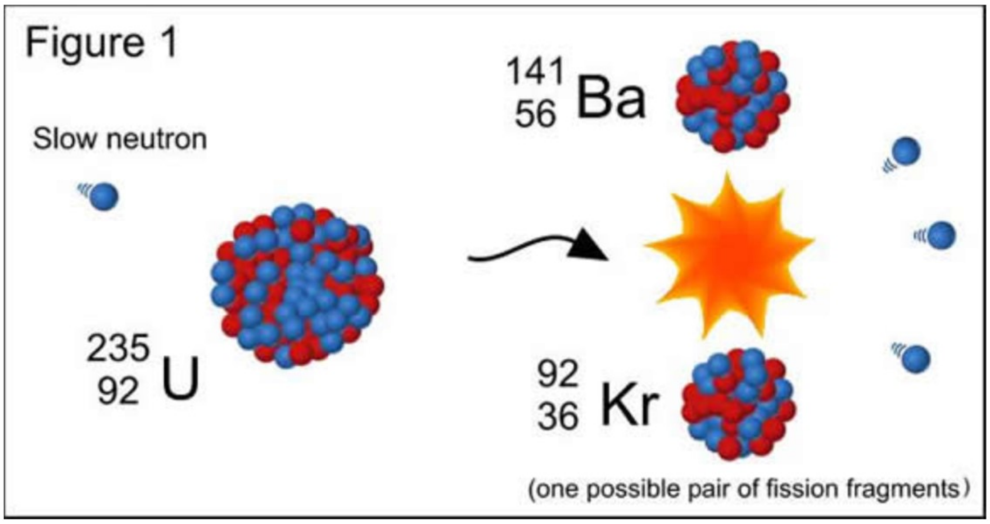
   a. Gamma rays have no mass and no charge, just energy

   b. Makes them the most destructive form of nuclear radiation

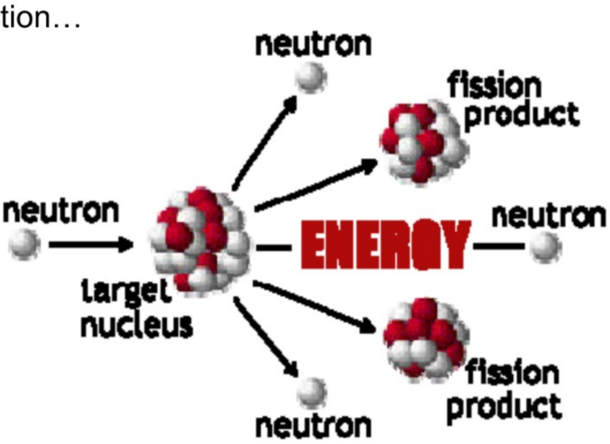


ARTICFICIAL TRANSMUTATION: change in the nucleus caused by the BOMBARDING OF A NUCLEUS with a HIGH ENERGY PARTICLE such as a neutron or alpha particle

Nuclear Fission: SPLITTING of the nucleus of an atom; LARGER PARTICLE(S) SPLIT into smaller particles

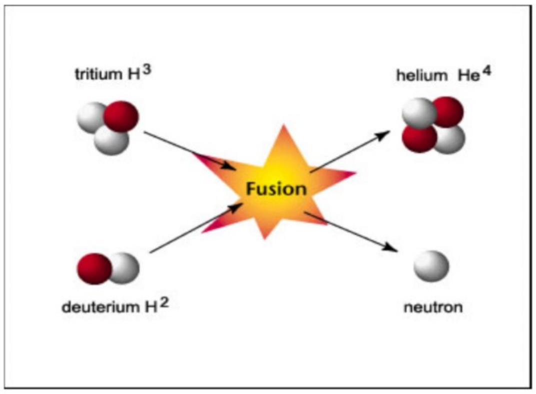


NOTE: A tremendous amount of ENERGY is also produced in the above nuclear reaction…



Disadvantages of Fission → 1) RADIOACTIVE WASTE
2) THERMAL POLLUTION

Nuclear Fusion: LIGHTER NUCLEI are COMBINED to produce heavier nucleus or nuclei



+ ENERGY

Another Example: $^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e}$

$^{1}_{1}\mathrm{H} + \mathrm{n} \rightarrow {}^{2}_{1}\mathrm{H}$

$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{2}\mathrm{He}$

$^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n}$

$^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H}$

$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n}$

$^{2}_{1}\mathrm{H} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H}$

Advantages of Fusion → 1) SIGNIFICANTLY more energy than even fission can produce, 2) no nuclear waste generated

Examples: The sun uses a fusion reaction to create energy (natural form of fusion);

Cold Fusion (human attempts to harness fusion as an energy source on Earth)

Disadvantages of Fusion → 1) Need to overcome extreme energy barriers, 2) difficult to control the reaction once accomplished

***NOTICE: MASSIVE AMOUNTS OF ENERGY IS PRODUCED AS A PRODUCT IN BOTH FUSION & FISSION REACTIONS!**

But where does the energy come from?

1. **BINDING ENERGY**:
    a. There is a tremendous amount of energy that holds the nucleons (protons and neutrons) so tightly together
    b. That energy is released whenever a nuclear reaction/rearrangement occurs
2. **MASS DEFECT**:
    a. The total mass of the product(s) is less than the original mass of the reactants after a nuclear reaction
    b. During a nuclear reaction, a certain amount of matter is converted into energy
    c. Einstein's equation,

$$E = mc^2 \qquad \text{(Energy = mass x speed of light)}$$

proved that when particles of matter are made to vibrate at the speed of light squared, they are converted into energy

The combination of these two phenomena is what accounts for the massive amounts of energy released during both fission and fusion.

HALF LIFE

Radioactive substances decay at a constant rate that is NOT DEPENDENT ON any other factors such as TEMPERATURE, PRESSURE, OR CONCENTRATION. It is impossible to predict when an unstable nucleus will decay because this is a completely RANDOM PROCESS. The only thing that can be determined is the number of unstable nuclei that will decay in a given time. Therefore, **half life,** OR THE TIME IS TAKES FOR HALF OF THE MASS TO DECAY, is a very important concept in nuclear chemistry. **Note:** half life varies per substance – see TABLE N (below) – this table is in your Reference Tables!

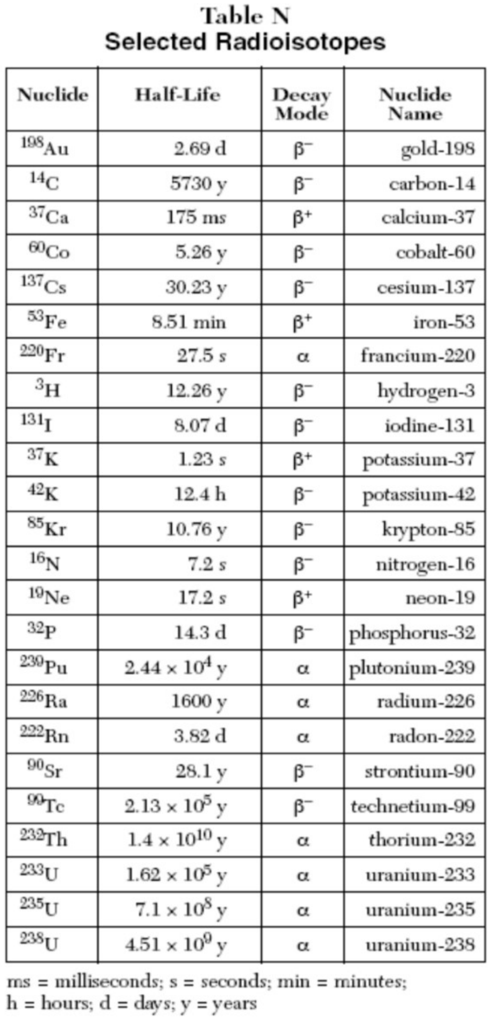


Table N
Selected Radioisotopes

Nuclide	Half-Life	Decay Mode	Nuclide Name
^{198}Au	2.69 d	β^-	gold-198
^{14}C	5730 y	β^-	carbon-14
^{37}Ca	175 ms	β^+	calcium-37
^{60}Co	5.26 y	β^-	cobalt-60
^{137}Cs	30.23 y	β^-	cesium-137
^{53}Fe	8.51 min	β^+	iron-53
^{220}Fr	27.5 s	α	francium-220
^{3}H	12.26 y	β^-	hydrogen-3
^{131}I	8.07 d	β^-	iodine-131
^{37}K	1.23 s	β^+	potassium-37
^{42}K	12.4 h	β^-	potassium-42
^{85}Kr	10.76 y	β^-	krypton-85
^{16}N	7.2 s	β^-	nitrogen-16
^{19}Ne	17.2 s	β^+	neon-19
^{32}P	14.3 d	β^-	phosphorus-32
^{239}Pu	2.44×10^4 y	α	plutonium-239
^{226}Ra	1600 y	α	radium-226
^{222}Rn	3.82 d	α	radon-222
^{90}Sr	28.1 y	β^-	strontium-90
^{99}Tc	2.13×10^5 y	β^-	technetium-99
^{232}Th	1.4×10^{10} y	α	thorium-232
^{233}U	1.62×10^5 y	α	uranium-233
^{235}U	7.1×10^8 y	α	uranium-235
^{238}U	4.51×10^9 y	α	uranium-238

ms = milliseconds; s = seconds; min = minutes;
h = hours; d = days; y = years

Basically:

- ※ The SHORTER THE HALF LIFE of an isotope the LESS STABLE it is.
- ※ The LONGER THE HALF LIFE of an isotope the MORE STABLE it is.

Half Life Word Problems: see Table T for formulas!

t = total time elapsed
T = half-life (get from table N)

Number of Half -Life Periods (n):

$\boxed{n = t/T}$

Fraction Remaining = ½ ^ (t/T)

or

(½)^n

Example: Most Chromium atoms are stable, but Cr - 51 is an unstable isotope with a half -life of 28 days. T = 28 days

(a) What fraction of a sample of Cr-51 will remain after 168 days?

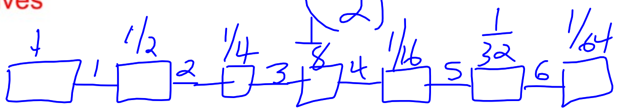
t = 168 days

n = t/T = 168 / 28 = 6 half-lives

$\left(\frac{1}{2}\right)^6$

fraction remaining = 0.015625

1/64



(b) If a sample of Cr-51 has an original mass of 52.0 g what mass will remain after 168 days?

$52 \times 0.015625 = \boxed{0.8125\text{ g}}$

(c) How much was present originally in a sample of Cr-51 if 0.75 mg remains after 168 days? (Hint: Calculate the number of half-lives, then use the "Fraction Remaining" formula from above.)

$2^6 = 64$ $64 \times .75 = \boxed{48\text{ g}}$

$n = \frac{t}{T}$

$\text{Frac remaining} = \left(\frac{1}{2}\right)^n = (.5)^n$

$\text{original sample} = \frac{\text{sample left}}{\text{fraction remaining}}$

Half-Life Practice Problems

1. Which of the radioisotopes from Table N has the longest half-life?

Th-232

2. Which of the radioisotopes from Table N has the shortest half-life?

Ca-37

3. What mass of a 100g sample of C-14 will remain after approximately 23,000 years?

$n = \frac{23{,}000}{5715} = 4$

$(.5)^4 = 0.0625$

$\boxed{100} \xrightarrow{1} \boxed{50} \xrightarrow{2} \boxed{25} \xrightarrow{3} \boxed{12.5} \xrightarrow{4} \boxed{6.25}$

$\text{Mass left} = 0.0625 \times 100g = 6.25g \text{ left}$

4. If 1.25 g of I-131 remains after 40.4 days, what was the mass of the original sample?

$n = \frac{40.4}{8.021} = 5.04$

$\text{Fract. Remain} = (.5)^n = (.5)^{5.04} = 0.030396$

$\text{Original Sample} = \frac{\text{sample left}}{\text{fract. Remain.}} = \frac{1.25}{0.030396} = \boxed{41.1g}$

5. How many half-lives will U-238 go through in 2.255 x 10^9 years?

$n = \frac{2.255 \times 10^9}{4.47 \times 10^9} = 0.5$

6. What percentage of a sample of Ra-226 will remain after 3,200 years?

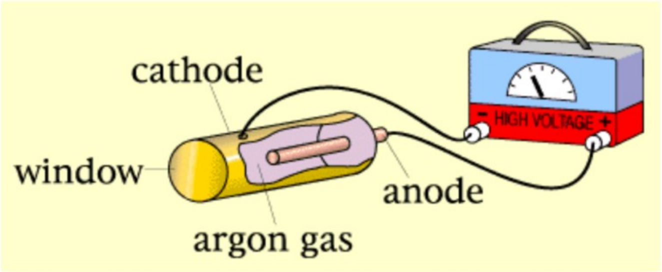
$n = \frac{3200}{1599} = 2 \quad (.5)^2 = 0.25 \approx 25\%$

7. What happens to the half-life of K-42 after 12.4 hours?

Nothing

Graphing Half-Life Data:

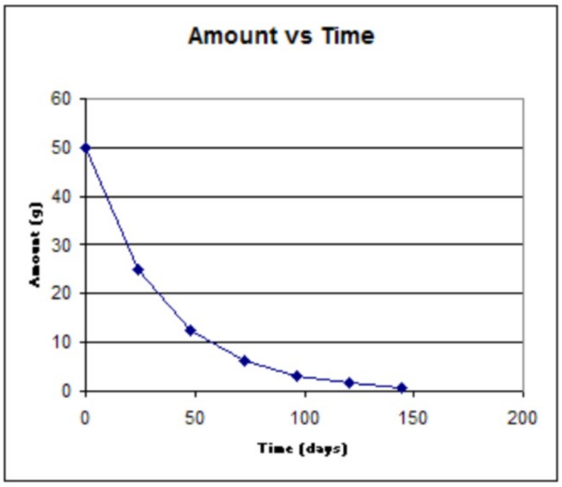
How do we detect something we can't see like the decay of a radioactive isotope? As a radioactive substance decays something called a **Geiger counter** can be used to record the individual decay events. It consists of a metal tube filled with argon or neon and is kept at low pressure. Into the center of this tube a wire has been anchored with high voltage set up between the wire and the tube. When ionizing particles enter this tube, it ionizes the entrapped gas and causes an electrical pulse. By adding up the number of pulses, the intensity of radiation can be detected.



When the data from a Geiger counter is graphed it can be used to determine the half life of an isotope:

Steps to determine half life from a graph:

1) Draw a vertical line (anywhere from one y value on the curve to half its y -value)
2) Now turn 90 degrees and draw a horizontal line (to the right) over to the curve → horizontal distance is the half life for that particular substance



Example: What is the half life of the substance illustrated in the above graph?

Approx. 25 days

Present Day Uses of Particular Radioisotopes:

Carbon-14 → DATING (not that kind, radioactive)

Uranium-238 to Lead-206 → NUCLEAR ENERGY

MEDICINE

Isotopes used in Medicine

Many radioisotopes are made in nuclear reactors, some in cyclotrons. Generally neutron-rich ones and those resulting from nuclear fission need to be made in reactors, neutron-depleted ones are made in cyclotrons. There are about 40 activation product radioisotopes and five fission product ones made in reactors.

REACTOR RADIOISOTOPES (half-life indicated)

Bismuth-213 (46 min): Used for targeted alpha therapy (TAT), especially cancers.

Chromium-51 (28 d): Used to label red blood cells and quantify gastro-intestinal protein loss.

Cobalt-60 (5.27 yr): Formerly used for external beam radiotherapy, now used more for sterilizing

Iodine-131 (8 d)*: Widely used in treating thyroid cancer and in imaging the thyroid; also in diagnosis of abnormal liver function, renal (kidney) blood flow and urinary tract obstruction. A strong gamma emitter, but used for beta therapy.

Iridium-192 (74 d): Used to treat head and breast cancer

Molybdenum-99 (66 h)*: Used as the 'parent' in a generator to produce technetium-99m.

Technetium-99m (6 h): Used to image the skeleton and heart muscle in particular, but also for brain, thyroid, lungs (perfusion and ventilation), liver, spleen, kidney (structure and filtration rate), gall bladder, bone marrow, salivary and lacrimal glands, heart blood pool, infection and numerous specialised medical studies. Produced from Mo-99 in a generator.