Nuclear Chemistry

Unit 13

Unit Objectives - Nuclear Chemistry

- Review & Atomic Nuclei
  - Rutherford's Gold Foil Experiment - Nucleons
  - Nuclide Representation
- Nuclear Change
  - Radioactive Decay
  - Natural/Artificial Transmutation
  - Nuclear Fission & Fusion
  - Half-Life
  - Nuclear Energy & Waste
- Uses of Nuclear Chemistry
  - Medical, Dating, Power
- Radioactive Decay Activity

Topic 1 – Review & Atomic Nuclei

Rutherford’s Gold Foil Experiment

- What do you remember about Rutherford's experiments?
  - Observations
  - Conclusions

Topic 2 - Risks/Benefits

Concerned with chemistry taking place in the nuclei of atoms (stability)

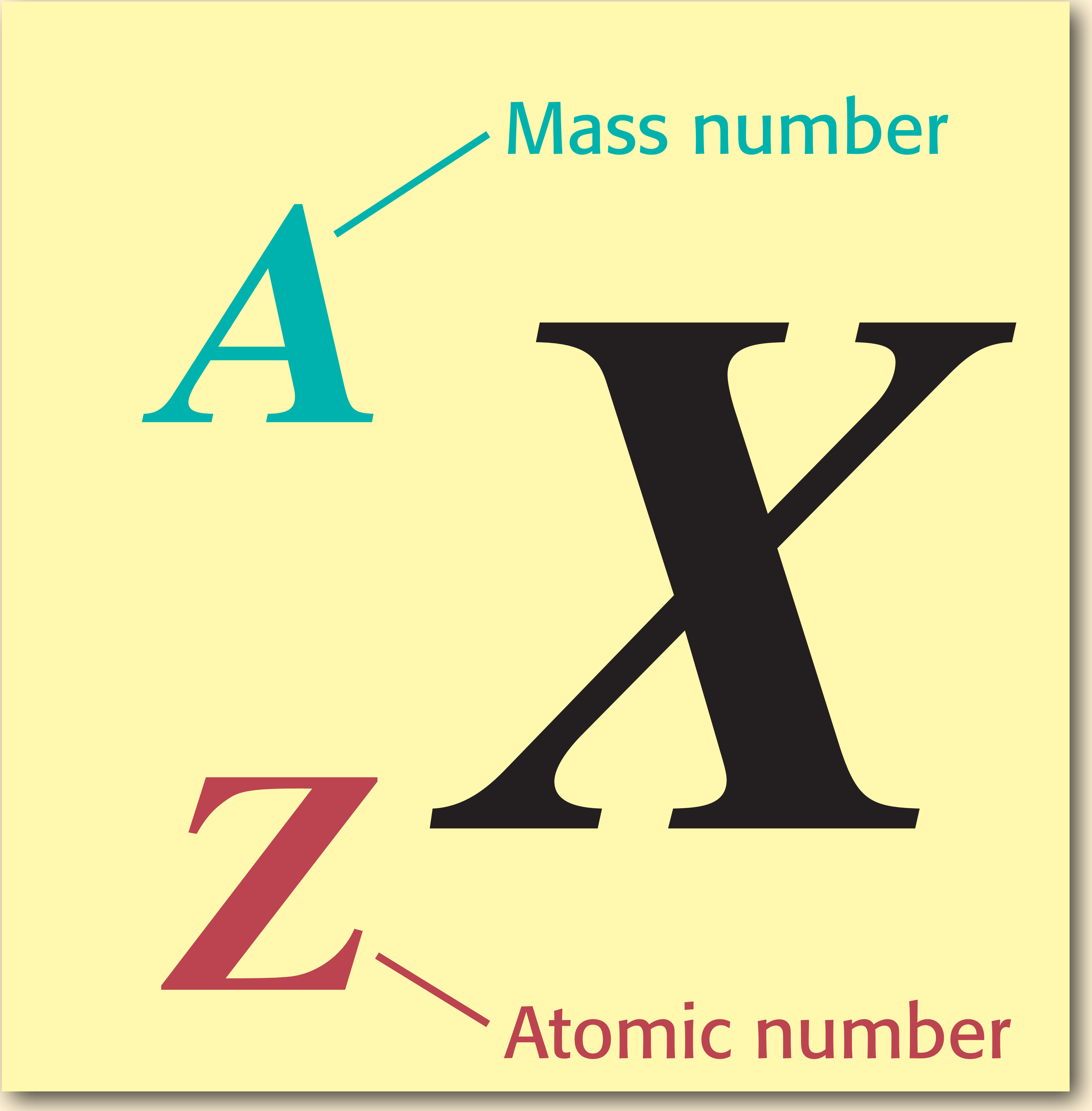
Nuclide Representation

- Nuclei can be represented in two ways:

1. The symbol (***X***) is shown with two numbers on the top and bottom left of it.

A = Mass number (total # of protons and neutrons)

Z = Atomic number (# of protons)



$^{122}_{52}Te$	$^{124}_{52}Te$	$^{128}_{52}Te$
70 neutrons 52 protons	72 neutrons 52 protons	76 neutrons 52 protons

2. The element name is given followed by the Mass Number

Radium-228 *or* **Ra-228**

Nuclear Stability

- Nuclei that have mass numbers >209 and atomic numbers > 83 are <u>*never*</u> stable.

Topic 3 – Nuclear Change & Decay

Radioactive Decay - Only a few types of nuclear changes occur.

- **Radioactivity** - emission of particles and energy (electromagnetic) to make a more stable nucleus.
- Changing MASS into ENERGY!! (And lots of it)

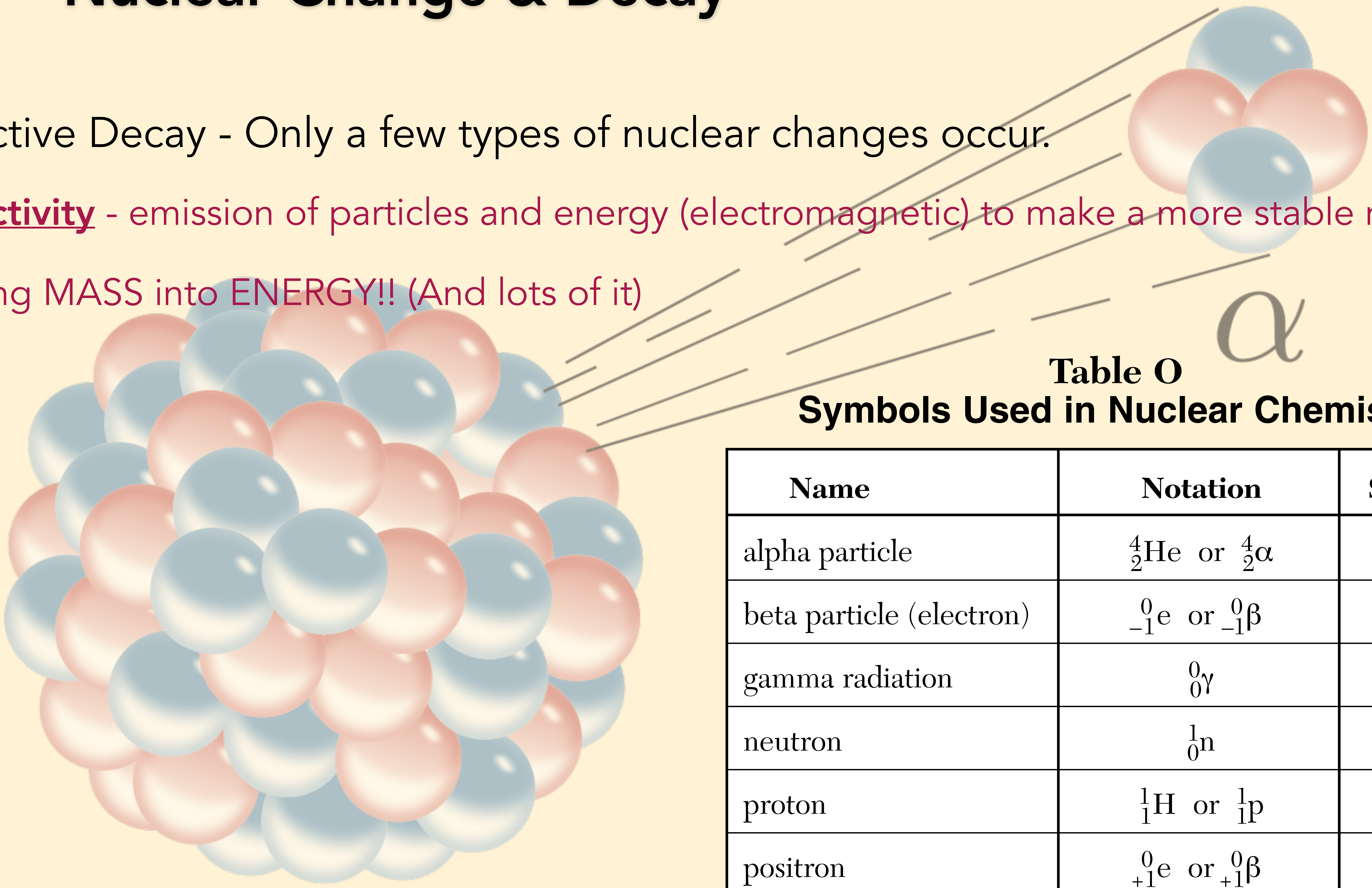


Table O
Symbols Used in Nuclear Chemistry

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

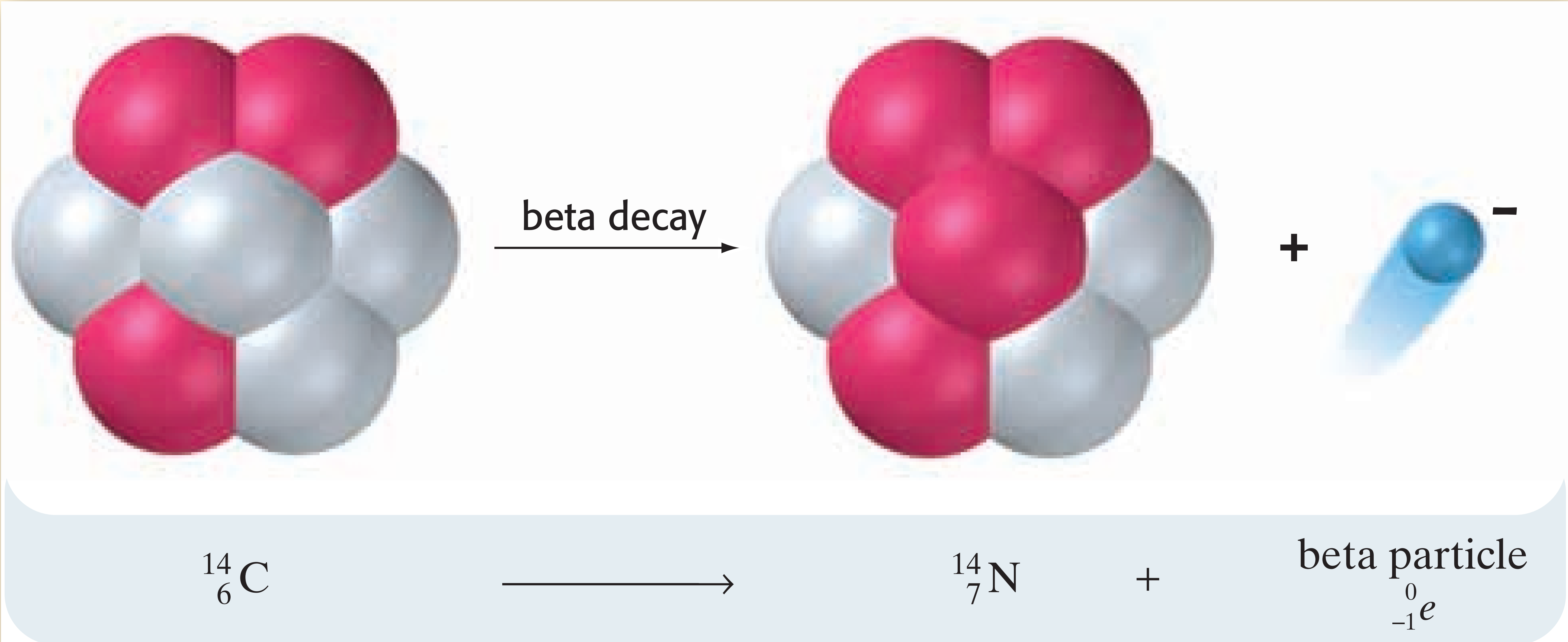
Beta Decay

Converting Neutrons into Protons

If an isotope has too many neutrons, the nucleus will decay and emit a high-energy electron, called a **beta particle**.

$$ {}^{1}_{0}n \xrightarrow{\text{beta decay}} {}^{1}_{+1}p + {}^{0}_{-1}e $$

Changes a **neutron into a proton =** atomic number increases by one.



Electron Capture - *Gamma Radiation*

Converting Protons into Neutrons

- If a nucleus has too many protons, it may capture an electron from the atom.
- Decreases the atomic number by one. The mass number stays the same.

$$ {}^{1}_{+1}p + {}^{0}_{-1}e \xrightarrow{\text{electron capture}} {}^{1}_{0}n + \Upsilon $$

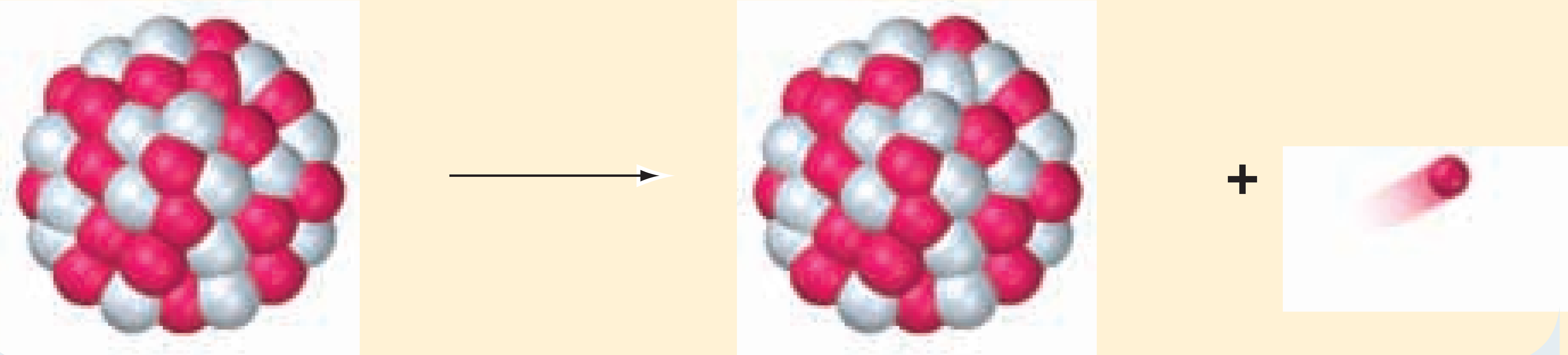
Υ = gamma rays

When the nucleus stabilizes, it releases energy in the form of gamma rays.

Positron Emission

- Some nuclei that have too many protons an become stable by emitting positrons = the antiparticles of electrons.

$$ {}^{1}_{+1}p \xrightarrow{\text{positron emission}} {}^{1}_{0}n + {}^{0}_{+1}e $$



$$ {}^{49}_{24}\text{Cr} \longrightarrow {}^{49}_{23}\text{V} + \underset{\text{positron}}{{}^{0}_{+1}e} $$

Alpha Particle Emission

- Unstable nuclei can decay by emitting an alpha (α) particle

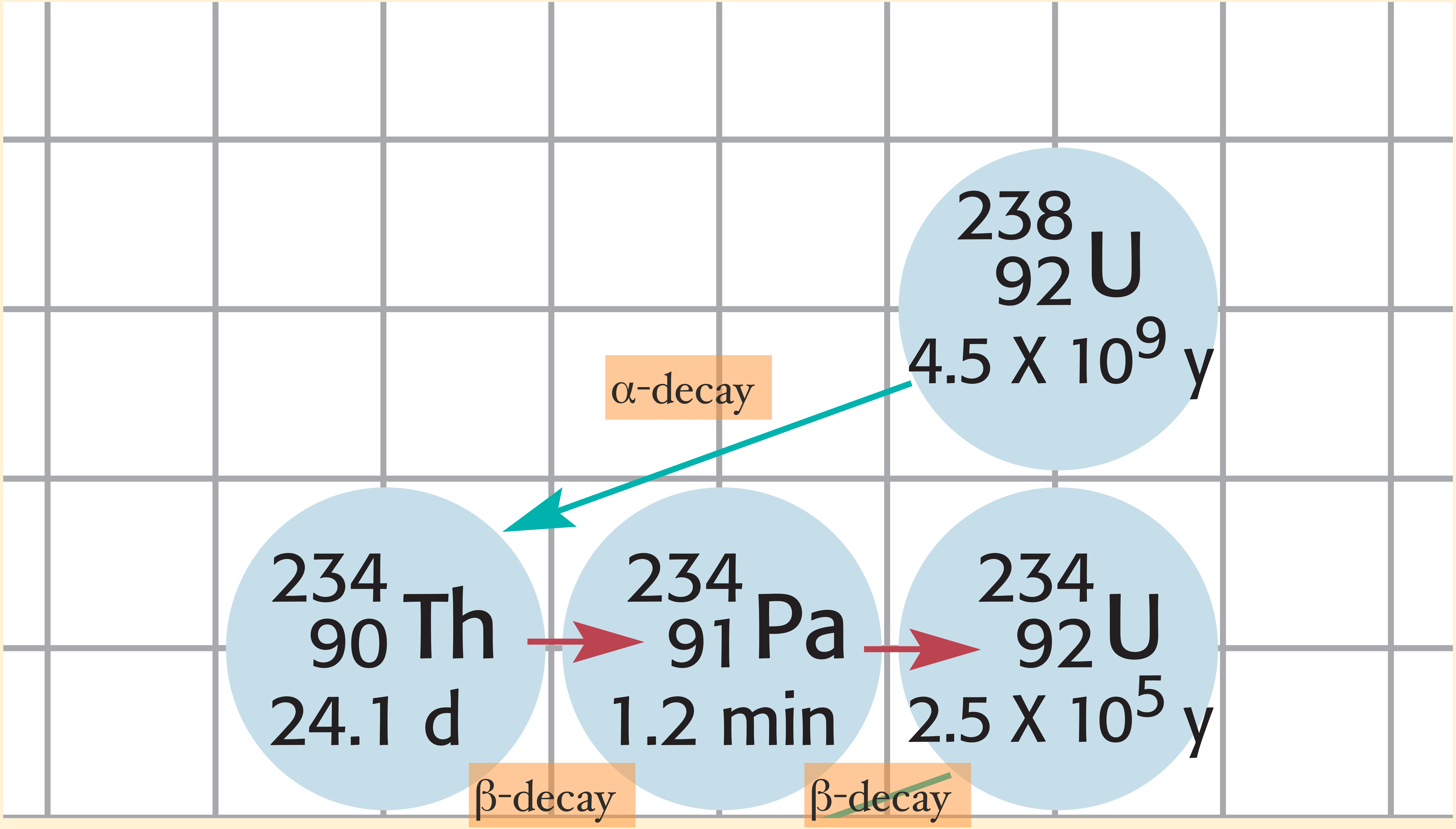
Particle	Mass (amu)	Charge	Symbol
α particle (He-4 nucleus)	4.001 474 92	+2	$\alpha, \alpha^{2+}, {}^{4}_{2}He$

- Atomic number decreases by two and mass number decreases by 4.

$$ {}^{238}_{92}U \xrightarrow{\text{alpha decay}} {}^{234}_{90}Th + {}^{4}_{2}He $$

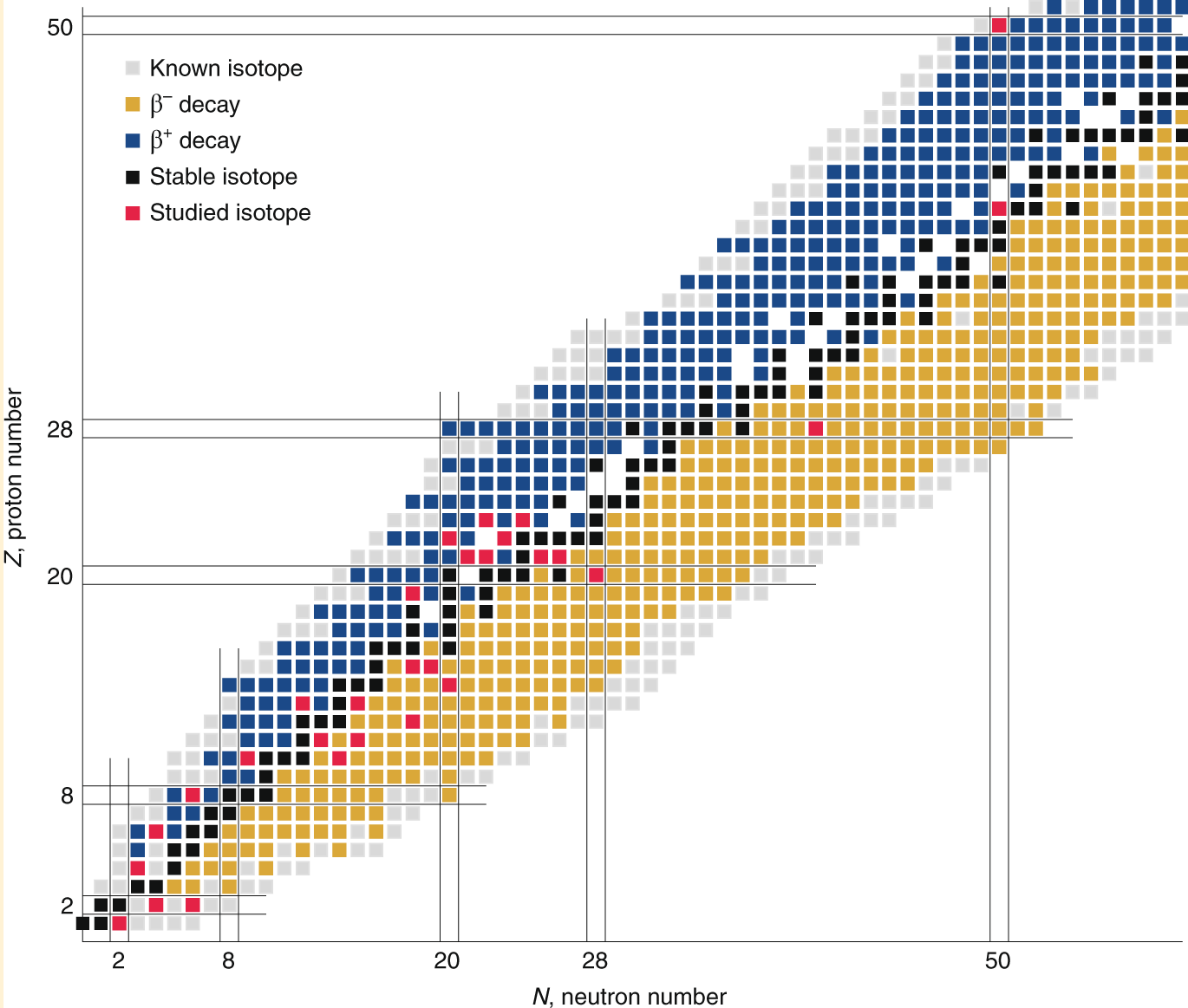
- Many heavy metals (like Uranium-238) go through a series of reactions called a decay series.

Decay Series



Stability Curve

- A neutron:proton ratio between 1.5 and 1.0 exists for stable nuclei.
- Decay will occur in such a way as to return a nucleus to the band (line) of stability.
- If Z > 83, the nuclide is radioactive.



Section Review

Which symbol represents a nuclide with 16 protons and 18 neutrons?

(1) $^{34}_{16}Se$ **(3)** $^{34}_{16}S$

(2) $^{16}_{18}Se$ **(4)** $^{18}_{16}S$

Which radioactive emission has a charge of +2 and a mass of 4 amu?

(1) alpha particle **(3)** positron

(2) beta particle **(4)** gamma ray

When an atom emits an alpha particle, its mass number

(1) decreases by 2. **(3)** decreases by 4.

(2) increases by 2. **(4)** increases by 4.

Section Review

Examine the following nuclear equation.

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

This radioactive decay is an example of

(1) positron emission.

(2) beta decay.

(3) electron capture.

(4) alpha decay.

Which describes a positron?

(1) same mass and charge as an electron

(2) mass of a proton and a +1 charge

(3) mass of an electron and a +1 charge

(4) heaviest subatomic particle

Section Review

What kind of nuclear reaction is shown below?

$$^{51}_{24}\text{Cr} + {}^{0}_{-1}e \longrightarrow {}^{51}_{23}\text{V} + \gamma$$

(1) alpha-decay
(2) beta-decay
(3) positron emission
(4) electron capture

Below is an example of:

$$^{49}_{24}\text{Cr} \longrightarrow {}^{49}_{23}\text{V} + {}^{0}_{+1}e$$

(1) alpha-decay
(2) beta-decay
(3) positron emission
(4) electron capture

Radioactive Decay Summary

- Beta Decay - neutrons to protons

$$ {}^{1}_{0}n \xrightarrow{\text{beta decay}} {}^{1}_{+1}p + {}^{0}_{-1}e $$

- Positron Emission - protons to neutrons

$$ {}^{1}_{+1}p \xrightarrow{\text{positron emission}} {}^{1}_{0}n + {}^{0}_{+1}e $$

- Electron Capture - protons to neutrons

$$ {}^{1}_{+1}p + {}^{0}_{-1}e \xrightarrow{\text{electron capture}} {}^{1}_{0}n $$

- Alpha Particle Emission - loss of a Helium nucleus

$$ {}^{238}_{92}\mathrm{U} \xrightarrow{\text{alpha decay}} {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} $$

Particle Review

Particle	Mass (amu)	Charge	Symbol	Stopped by
Proton	1.007 276 47	+1	$p, p^+, {}_{+1}^{1}p, {}_{1}^{1}\mathrm{H}$	a few sheets of paper
Neutron	1.008 664 90	0	$n, n^0, {}_{0}^{1}n$	a few centi-meters of lead
β particle (electron)	0.000 548 580	–1	$\beta, \beta^-, {}_{-1}^{0}e$*	a few sheets of aluminum foil
Positron†	0.000 548 580	+1	$\beta^+, {}_{+1}^{0}e$*	same as electron
α particle (He-4 nucleus)	4.001 474 92	+2	$\alpha, \alpha^{2+}, {}_{2}^{4}\mathrm{He}$	skin or one sheet of paper
Gamma ray	0	0	γ	several centi-meters of lead

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

Topic 4 - Nuclear Equations

Spontaneous/Natural Transmutation

*****do not require an outside energy source**

- One atom on the left hand side of the reaction
- Forms multiple particles

Artificial Transmutation

*****need an external energy source to proceed**

- Multiple atom/particle on the left hand side of the reaction
- Forms multiple particles or a single product

Transmutations

- In the Middle Ages, many early chemists *(Alchemists)*tried to change, or *transmute*, ordinary metals into gold. Although not successful, they did make many other important discoveries.

- *Transmutation*: where one element changes into another is a nuclear reaction!
  - It changes the nucleus of an atom and therefore cannot be achieved by ordinary chemical reactions.

$$^{235}_{92}\mathrm{U} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{231}_{90}\mathrm{Th}$$

Natural Transmutation

Uranium-235 changes into Thorium-231 by an alpha decay.

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

Artificial Transmutation

Nitrogen-14 changes into Oxygen-17 by neutron bombardment.

Balancing Nuclear Equations

- **Notice**: MASS AND CHARGE MUST ALWAYS BALANCE

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

[238 = 234 + 4 mass balance]
[92 = 90 + 2 charge balance]

$$^{234}_{90}Th \longrightarrow ^{234}_{91}Pa + ^{0}_{-1}e$$

[234 = 234 + 0 mass balance]
[90 = 91 + (–1) charge balance]

- **Remember**: whenever the atomic number changes, the identity of the element changes.

Balancing Nuclear Equation Practice

$$^{218}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + ?$$

$$^{142}_{61}\text{Pm} + ? \longrightarrow {}^{142}_{60}\text{Nd}$$

$$^{253}_{99}\text{Es} + {}^{4}_{2}\text{He} \longrightarrow {}^{1}_{0}n + ?$$

Write the balanced nuclear equation that shows how sodium-22 changes into neon-22.

Topic 5 – Half Life / Uses

<u>Half-Life</u>: the time required for half of a sample of a radioactive substance to disintegrate by radioactive decay or natural processes.

- The half-life of a radioactive isotope is a **constant value** and is not influenced by any external conditions.
    - Geologic dating
    - Smoke detectors
    - Art Forgeries
    - Medicine

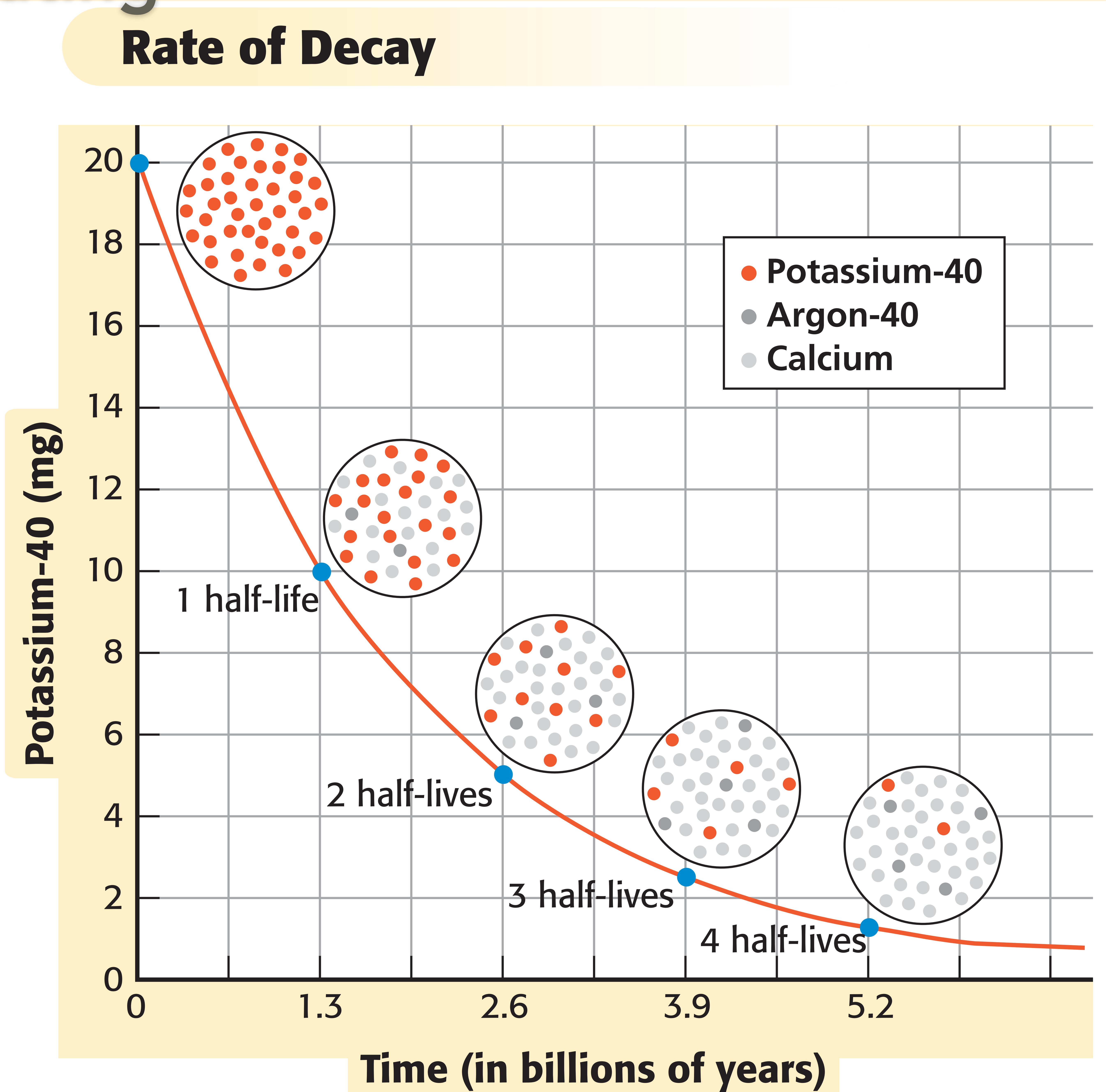
Rate of Decay - Geologic Dating

K-40 has a 1/2-life of 1.2 *billion* years

$$^{40}_{19}K \longrightarrow ^{40}_{18}Ar + ^{0}_{+1}e$$

$$^{40}_{19}K \longrightarrow ^{40}_{20}Ca + ^{0}_{-1}e$$

Used to tell the age of ancient rocks and minerals.



Carbon-14: How it works

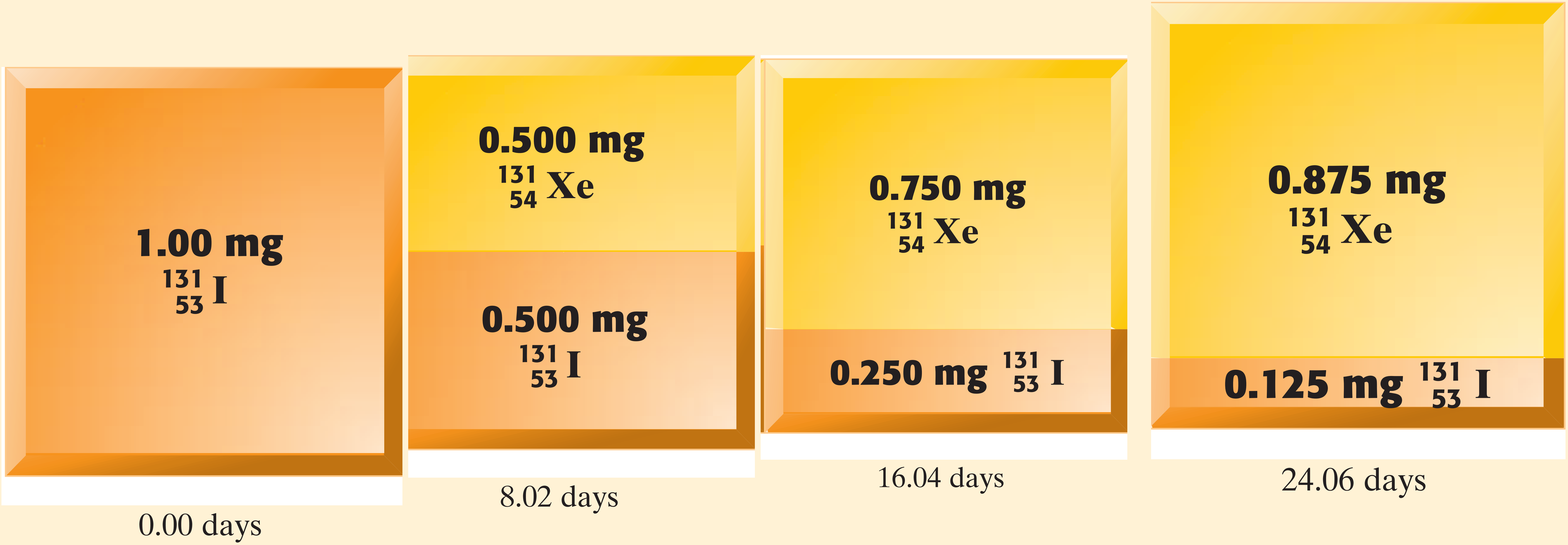
- Nearly all of the carbon on Earth is present as the stable isotope carbon-12. A very small percentage of the carbon in Earth's crust is carbon-14. ONLY WORKS FOR LIVING THINGS OR THINGS THAT WERE ALIVE.

C-14 half-life is 5715 years $^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$

If we start with 100 grams of C-14, how much will we have in:

1 half-life?	1/2 x 100 = 50	5715 years: 50 grams
3 half-lives?	1/2 x 1/2 x 1/2 = 1/8 x 100	17,145 years: 12.5 grams
5 half-lives?	1/2 x 1/2 x 1/2 x 1/2 x 1/2 = 1/32 x 100	28,575 years: 3.12 grams

- The more unstable the nuclide is, the shorter its half-life is and the faster it decays (*General Rule*).



Half-Life Review Questions

After 4797 years, how much of an original 0.250 g sample of radium-226 remains? Its half-life is 1599 years.

number of half-life periods = t/T = 4797/1599 = 3

1/2 x 1/2 x 1/2 = 1/8 * 0.250 = 0.0313 g

What mass of radioactive isotope will remain unchanged from a 200-gram sample of iodine-131 after 40.4 days?

(1) 25 grams
(2) 12.5 grams
(3) 6.25 grams
(4) 3.125 grams

An artifact has one-sixteenth of the ratio of carbon-14 to carbon-12 that is found in a modern-day object. How many half-lives have elapsed?

(1) one
(2) two
(3) three
(4) four

Approximately what fraction of an original Co-60 sample remains after 21 years?

1) $\frac{1}{8}$ 2) $\frac{1}{4}$ 3) $\frac{1}{2}$ 4) $\frac{1}{16}$

As a sample of the radioactive isotope ^{131}I decays, its half-life

1) increases 2) decreases 3) remains the same

What is the half-life and decay mode of Rn-222?

1) 1.91 days and alpha decay
2) 3.82 days and beta decay
3) 3.82 days and alpha decay
4) 1.91 days and beta decay

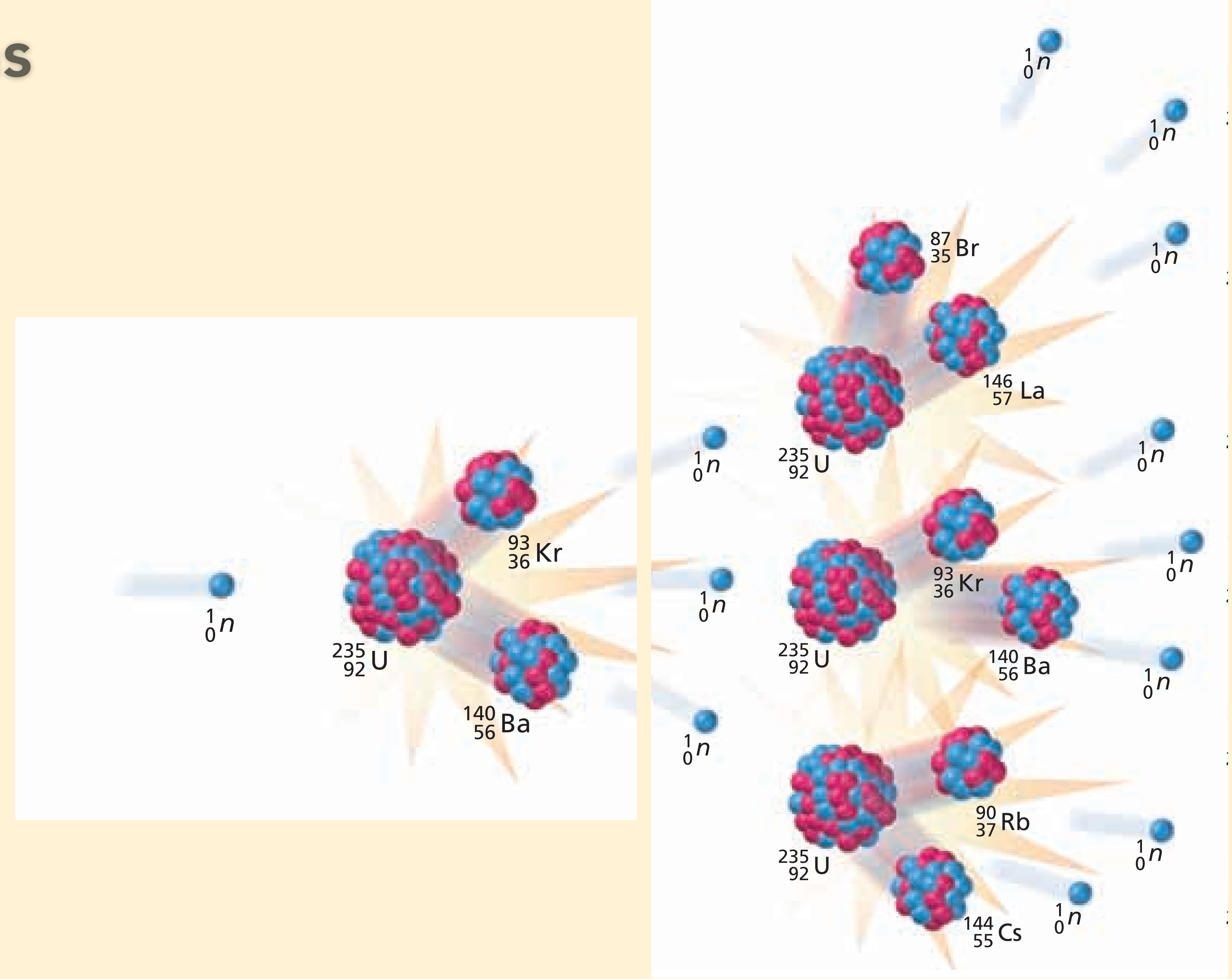
Topic 6 - Fission & Fusion Reactions

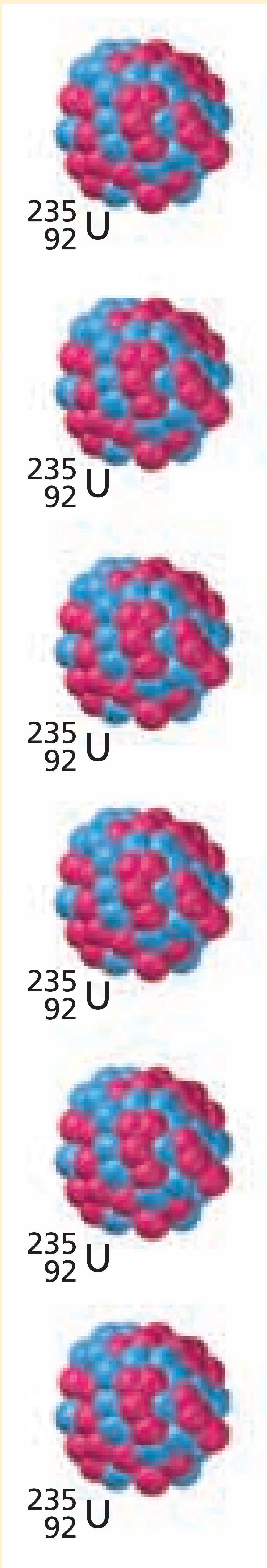
FISSION: the splitting of the nucleus of a large atom into two or more fragments.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \xrightarrow{\text{nuclear fission}} {}^{93}_{36}\mathrm{Kr} + {}^{140}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}n$$

- Most fission reactions happen artificially by bombarding nuclei with neutrons.
- *Chain reaction*!

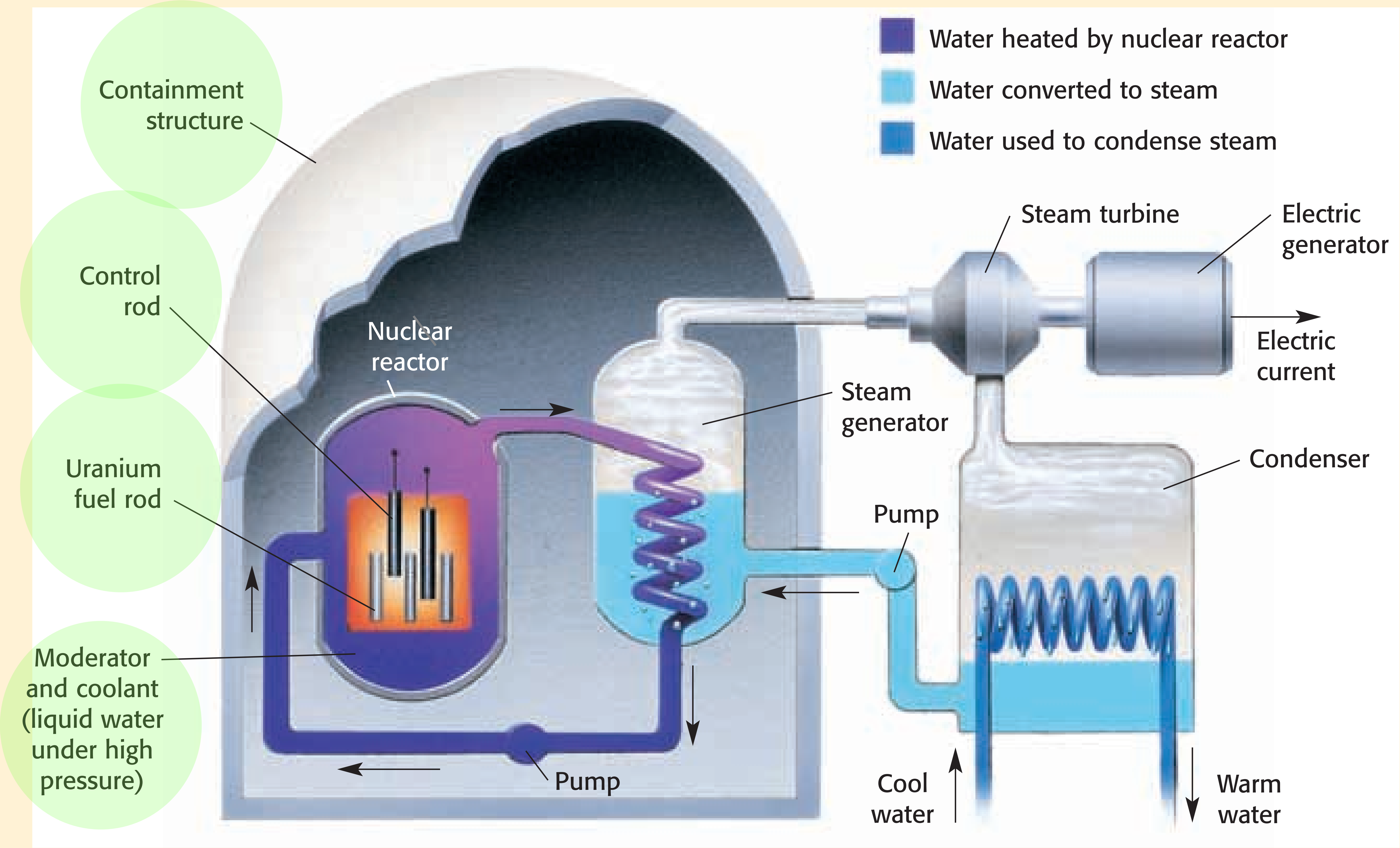
Chain Reactions





Chain reactions will continue until there is no radioactive material capable of undergoing fission available.

Nuclear Reactors



- Fission reactions can produce large amounts of energy. The chain reactions need to be controlled within the reactor.

Fusion Reactions

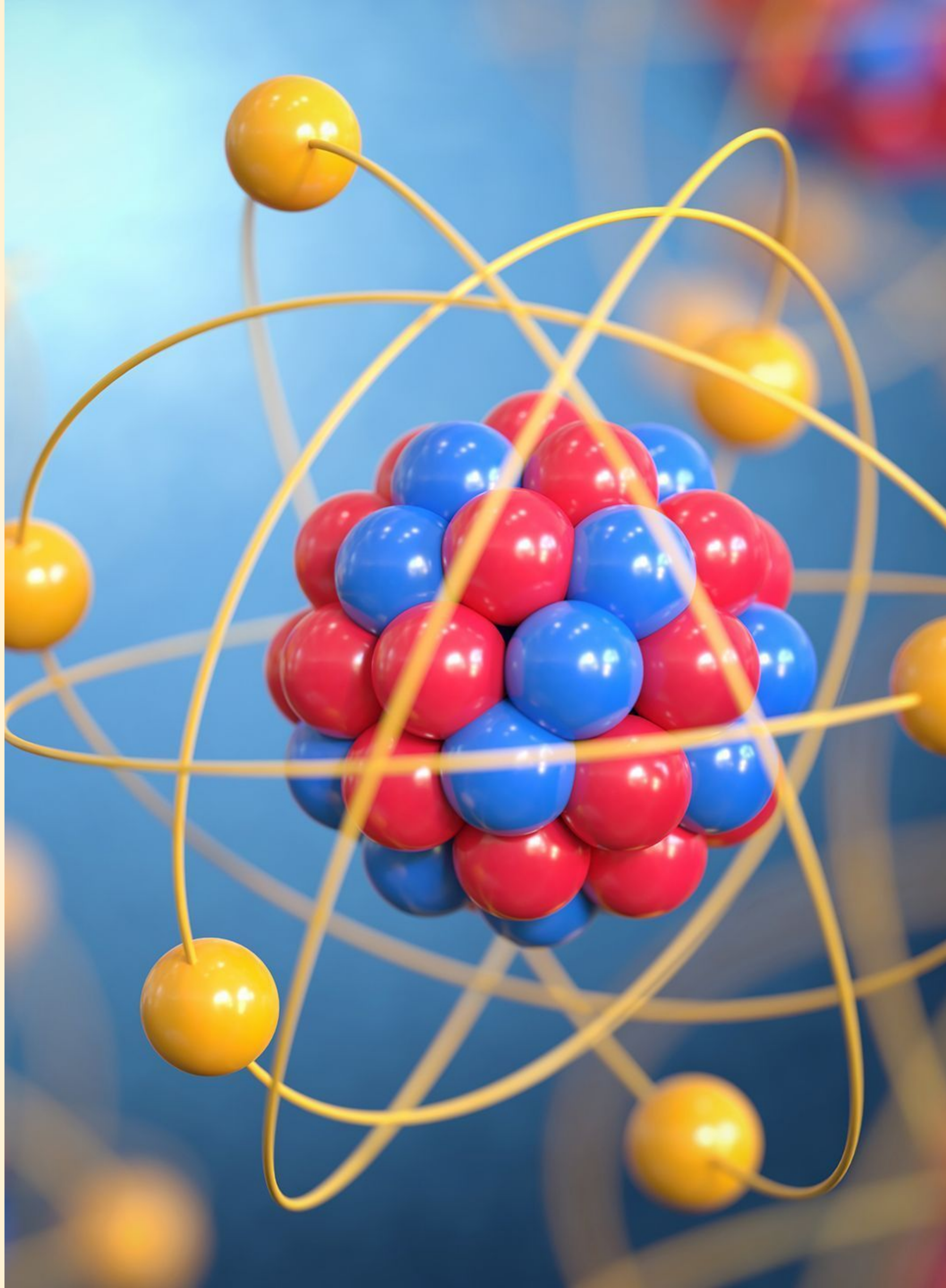
Fusion: the combination of the nuclei of small atoms to form a larger nucleus, a process that releases energy.

$$4\,{}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{\;\;0}_{+1}e.$$

- Fusion reactions release greater amounts of energy than fission reactions for the same mass of starting material.
- Very high temperatures are required to bring the nuclei together (1.5×10^{7} °C).
- Currently, the only place that fusion reactions take place are in stars (like our Sun).

Need to Know These Radioisotopes

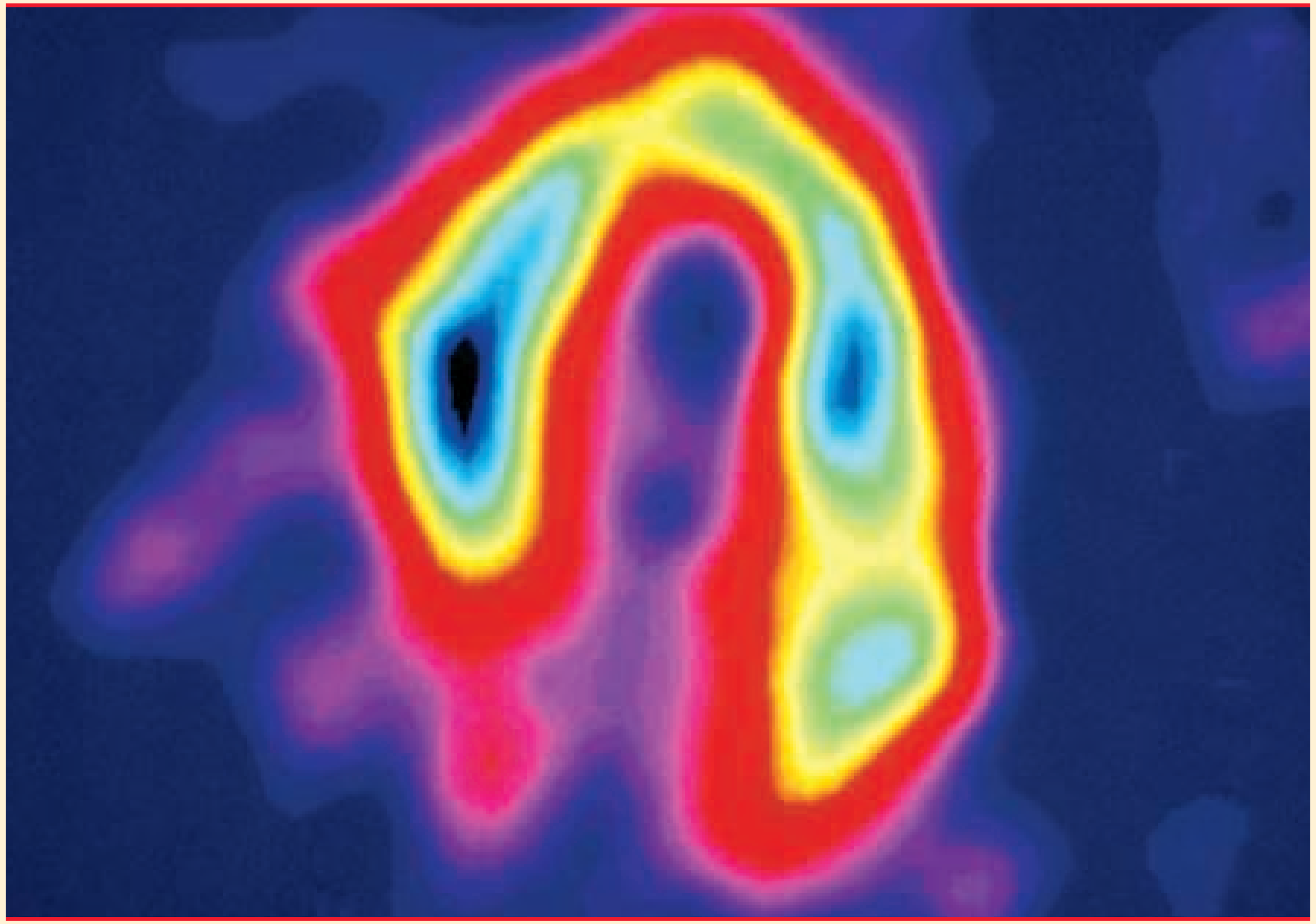
- ^{131}I = thyroid ailments
- ^{14}C = carbon dating of once living artifacts
- ^{238}U - ^{206}Pb = rock dating
- ^{60}Co = cancer treatment
- ^{99}Tc = tumor detection
- P-31 = trace uptake of phosphorus by plants
- U-235 = nuclear reactor fuel



Medical Uses for Nuclear Chemistry

- The person is given an injection of ***thallium-201***, which acts chemically like calcium and collects in the heart. As the ***thallium-201*** decays, low-energy gamma rays are emitted and are detected by a special camera that produces images.

This image reveals the size of the heart, how well the chambers are pumping, and whether there is any scarring of muscle from previous heart attacks.



Radioactive compounds used in medicine typically have very short half-lives so that they do not persist in the body.

Radiation Exposure

Table 3 **Effect of Whole-Body Exposure to a Single Dose of Radiation**

Dose (rem)	Probable effect
0–25	no observable effect
25–50	slight decrease in white blood cell count
50–100	marked decrease in white blood cell count
100–200	nausea, loss of hair
200–500	ulcers, internal bleeding
> 500	death