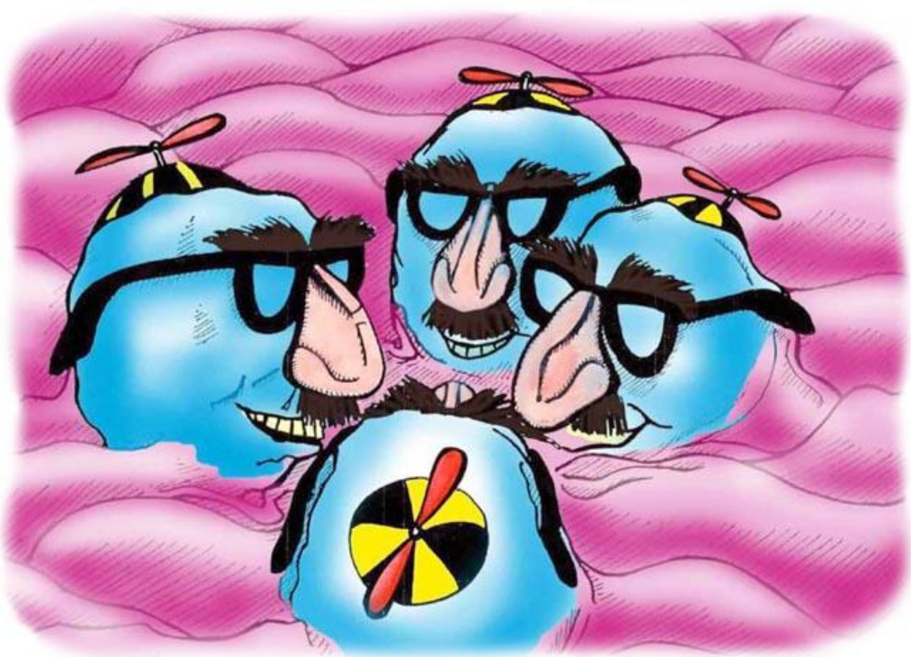
Ch 19 Radiactivity and Nuclear Chemistry



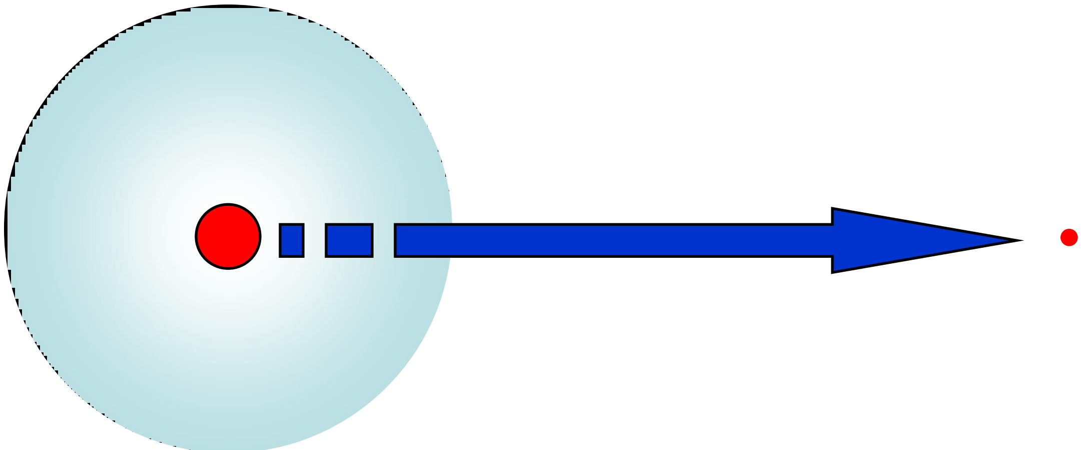
At a resolution of 10^{-24} metres, isolated clumps of strange matter pop briefly out of the quantum foam to debate the possible existence of particle physicists.

Modified by Dr. Cheng-Yu Lai

What Is Radioactivity?

- Radioactivity is the release of tiny, high-energy particles or gamma rays from an atom.

- Particles are ejected from the nucleus.



Nuclear Symbols

Mass number, A
($p^+ + n^o$)

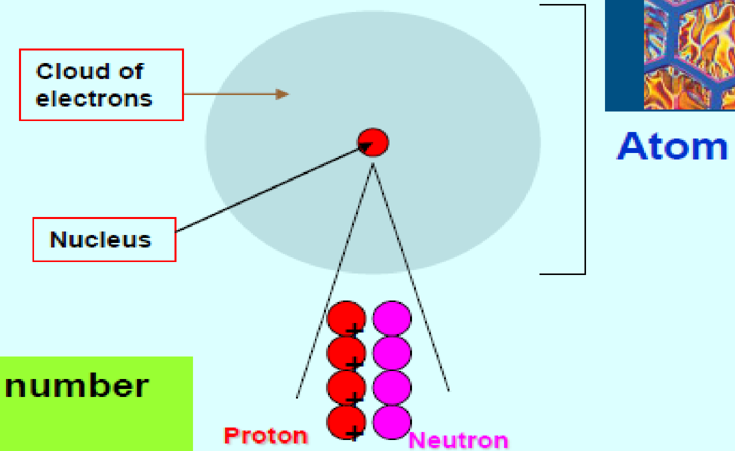
Element symbol

$$^{235}_{92}U$$

Atomic number, Z
(number of p^+)

- Atomic number = proton number
- Proton number = electron number
- mass number = proton number + neutron number

Review of Nucleus



- All atoms with the same atomic number belong to the **same element**.

- Atoms from the same element may have different numbers of neutrons, thus have **different mass numbers**.

$$^{A}_{Z}X \quad ^{B}_{Z}X \quad ^{C}_{Z}X \quad ^{D}_{Z}X$$

- Atoms with the same atomic number but different mass numbers are called **isotopes**.

Nucleus —If not stable, called→ **Radioactive Nucleus** —namely→ **Radionuclide**

Radioactive nuclei spontaneously decompose (decay) with the evolution of energy

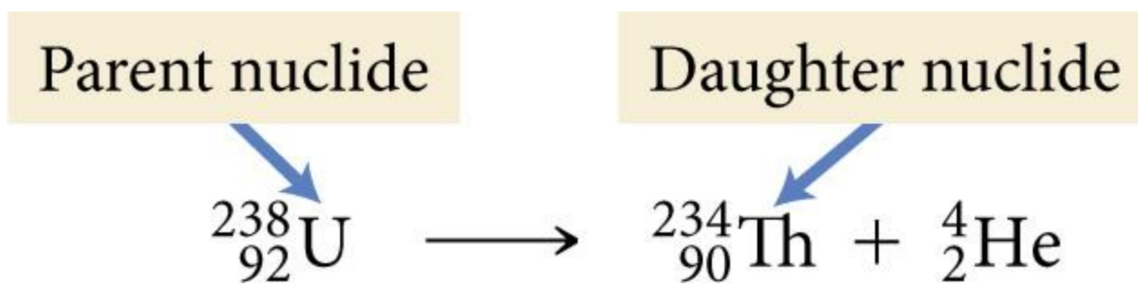
Radioactive isotopes are called radioisotopes.

Nuclear Reactions vs. Chemical Reactions

- In a chemical reaction
  - Only the outer electron configuration of atoms and molecules changes
  - There is no change to the nucleus
- In a nuclear reaction
  - Mass numbers may change
  - Atomic numbers may change
    - One element may be converted to another

Nuclear Equations

- In the nuclear equation, mass numbers and atomic numbers are conserved.
- We can use this fact to determine the identity of a daughter nuclide if we know the parent and mode of decay.



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

Nuclear Equations

- We describe nuclear processes with nuclear equations.
- Atomic numbers and mass numbers are conserved.
  - The sum of the atomic numbers on both sides must be equal.
  - The sum of the mass numbers on both sides must be equal.

Parent nuclide → Daughter nuclide

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

Reactants	Products
Sum of mass numbers = 238	Sum of mass numbers = 234 + 4 = 238
Sum of atomic numbers = 92	Sum of atomic numbers = 90 + 2 = 92

Balancing Nuclear Equations

$$\sum A_{reactants} = \sum A_{products}$$

235 + 1 = 142 + 91 + 3(1)

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3\,^{1}_{0}n$$

92 + 0 = 56 + 36 + 3(0)

$$\sum Z_{reactants} = \sum Z_{products}$$

Balancing Nuclear Equations

226 = 4 + $\underline{222}$

$$^{226}_{88}Ra \rightarrow {}^{4}_{2}\alpha + {}^{222}_{86}Rn$$

88 = 2 + $\underline{86}$

Atomic number 86 is radon, Rn

Five Modes of Radioactive Decay

- five modes of radioactive decay

1. Alpha (α) particle emission

Mass number is 4, charge is +2, atomic number 2

Symbol is $^{4}_{2}He$ or $^{4}_{2}\alpha$

When a nucleus emits an alpha particle, its mass number decreases by 4 and its atomic number decreases by 2

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

Five Modes of Radioactive Decay

2. Beta (β) particle emission

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

Example:

β particle

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e$$

131	=	131	+	0		Total mass number same
53	=	54	+	-1		Total atomic number same

3. Gamma (γ) radiation emission

γ Particle = $^{0}_{0}\gamma$

Five Modes of Radioactive Decay

4. Positron emission

Positron emission:

Positrons are the anti-particle of the electron

$$^{0}_{1}e$$

$$^{22}_{11}Na \rightarrow {^{0}_{1}e} + {^{22}_{10}Ne}$$

Positron emission converts a proton to a neutron

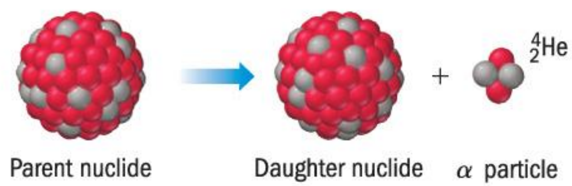
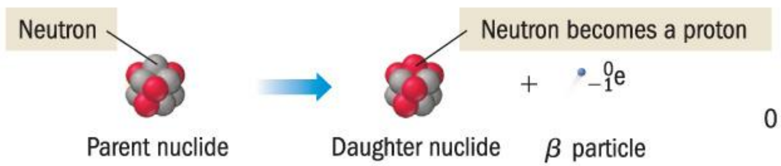
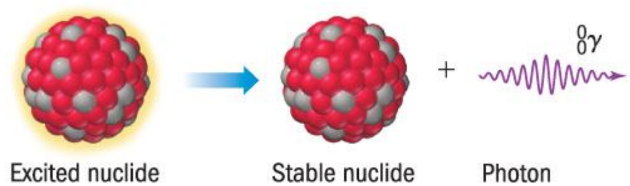
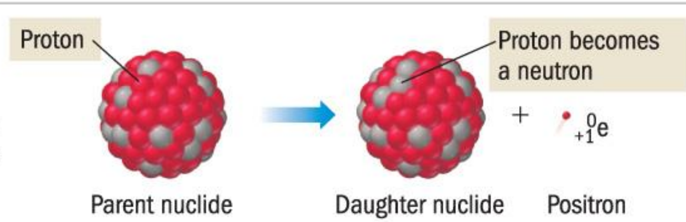
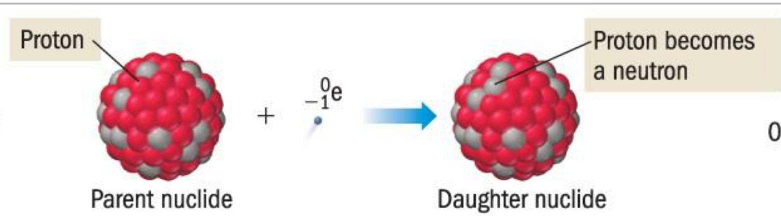
5. K-electron capture

Electron capture: (inner-orbital electron is captured by the nucleus)

$$^{201}_{80}Hg + {^{0}_{-1}e} \rightarrow {^{201}_{79}Au} + {^{0}_{0}\gamma}$$

Electron capture converts a proton to a neutron

TABLE 19.1 Modes of Radioactive Decay

Decay Mode	Process	Change in: *A*	Z	N/Z*	Example
α		−4	−2	Increase	$^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$
β		0	+1	Decrease	$^{228}_{88}Ra \longrightarrow ^{228}_{89}Ac + ^{0}_{-1}e$
γ		0	0	None	$^{234}_{90}Th \longrightarrow ^{234}_{90}Th + ^{0}_{0}\gamma$
Positron emission		0	−1	Increase	$^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^{0}_{+1}e$
Electron capture		0	−1	Increase	$^{92}_{44}Ru + ^{0}_{-1}e \longrightarrow ^{92}_{43}Tc$

* Neutron-to-proton ratio

Important Atomic Symbols

Particle	Symbol	Nuclear Symbol
proton	p^+	$^{1}_{1}H$ $^{1}_{1}p$
neutron	n^0	$^{1}_{0}n$
electron	e^-	$^{0}_{-1}e$
alpha	α	$^{4}_{2}\alpha$ $^{4}_{2}He$
beta	β, β^-	$^{0}_{-1}\beta$ $^{0}_{-1}e$
positron	β, β^+	$^{0}_{+1}\beta$ $^{0}_{+1}e$

EXAMPLE 18.2

Promethium ($Z = 61$) is essentially nonexistent in nature; all of its isotopes are radioactive. Write balanced nuclear equations for the decomposition of

(a) Pm-142 by positron emission.

(b) Pm-147 by beta emission.

(c) Pm-150 by alpha emission.

$${}^{0}_{1}e \quad {}^{0}_{-1}e \quad {}^{4}_{2}He$$

STRATEGY

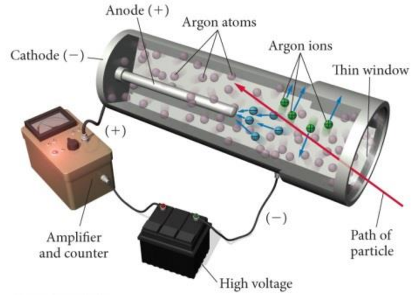
1. Recall the symbol of the particle emitted for the specified decay mode.
2. Balance mass number and atomic number.
3. Find the symbol of the product isotope in the periodic table by using its atomic number.

SOLUTION

(a) 1. particle emitted	positron: ${}^{0}_{1}e$
2. mass and atomic number balance	${}^{142}_{61}\text{Pm} \longrightarrow {}^{0}_{1}e + {}^{142}_{60}$
3. reaction	${}^{142}_{61}\text{Pm} \longrightarrow {}^{0}_{1}e + {}^{142}_{60}\text{Nd}$
(b) 1. particle emitted	β-particle: ${}^{0}_{-1}e$
2. mass and atomic number balance	${}^{147}_{61}\text{Pm} \longrightarrow {}^{0}_{-1}e + {}^{147}_{62}$
3. reaction	${}^{147}_{61}\text{Pm} \longrightarrow {}^{0}_{-1}e + {}^{147}_{62}\text{Sm}$
(c) 1. particle emitted	α-particle: ${}^{4}_{2}\text{He}$
2. mass and atomic number balance	${}^{150}_{61}\text{Pm} \longrightarrow {}^{4}_{2}\text{He} + {}^{146}_{59}$
3. reaction	${}^{150}_{61}\text{Pm} \longrightarrow {}^{4}_{2}\text{He} + {}^{146}_{59}\text{Pr}$

Rate of Radioactive Decay

- The rate of change in the amount of radioactivity is constant, and is different for each radioactive "isotope."
  - ✓ Change in radioactivity measured with Geiger counter
    - ➢ Counts per minute



- Each radionuclide had a particular length of time it required to lose half its radioactivity—a constant half-life.
  - ✓ We know that processes with a constant half-life follow **first order kinetic rate laws**.

- The rate of radioactive change was not affected by temperature.
  - ✓ In other words, radioactivity is not a chemical reaction!

Decay Kinetics

Decay occurs by first order kinetics (the rate of decay is proportional to the number of nuclides present)

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

N_0 = number of nuclides present initially

k = rate constant

N = number of nuclides remaining at time t

t = elapsed time

Calculating Half-life

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

$t_{1/2}$ = Half-life (units dependent on rate constant, k)

Sample Half-Lives

Half-Lives and Radiation of Some Naturally Occurring Radioisotopes		
Isotope	Half-life	Radiation emitted
Carbon-14	5.73×10^3 years	β
Potassium-40	1.25×10^9 years	β, γ
Radon-222	3.8 days	α
Radium-226	1.6×10^3 years	α, γ
Thorium-230	7.54×10^4 years	α, γ
Thorium-234	24.1 days	β, γ
Uranium-235	7.0×10^8 years	α, γ
Uranium-238	4.46×10^9 years	α

$$^{238}_{92}U \rightarrow ^{206}_{82}Pb + \ldots$$

If 1 atom of lead-206 is formed, must be 1 atom of uranium-238 is decayed.

Decay Kinetics

EXAMPLE 18.4

A tiny piece of paper taken from the Dead Sea Scrolls, believed to date back to the first century A.D., was found to have an activity per gram of carbon of 12.1 atoms/min. Taking A_o to be 15.3 atoms/min, estimate the age of the scrolls.

ANALYSIS

Information given:	A (12.1 atoms/min); A_o (15.3 atoms/min)
Information implied:	$t_{1/2}$ for C-14 (5730 y)
Asked for:	Age of the scrolls

STRATEGY

1. Find k by substituting into the equation relating half-life and rate constant for a first-order reaction.

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

2. Substitute into Equation 18.2 to find t.

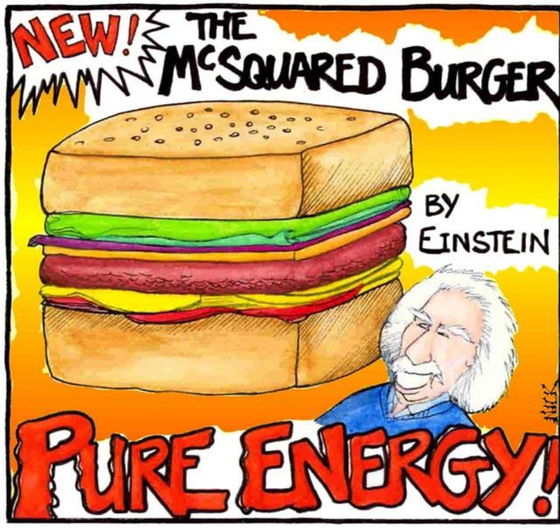
$$\ln \frac{A_o}{A} = kt$$

SOLUTION

1. k	$k = \frac{0.693}{5730\ y} = 1.21 \times 10^{-4}\ y^{-1}$
2. t	$\ln \frac{15.3\ \text{atoms/min}}{12.1\ \text{atoms/min}} = (1.21 \times 10^{-4}\ y^{-1})(t) \longrightarrow 0.235 = (1.21 \times 10^{-4}\ y^{-1})(t)$ $t = 1.94 \times 10^3\ y$ The scrolls do date back to the first century A.D.

Nonradioactive Nuclear Changes

- **Fission**
  – The large nucleus splits into two smaller nuclei.
- **Fusion**
  – Small nuclei can be accelerated to smash together to make a larger nucleus.
- **Both fission and fusion release enormous amounts of energy.**
  ✓ Fusion releases more energy per gram than fission.



Energy and Mass

Nuclear changes occur with small but measurable losses of mass. The lost mass is called the mass defect, and is converted to energy according to Einstein's equation:

$$\Delta E = \Delta mc^2$$

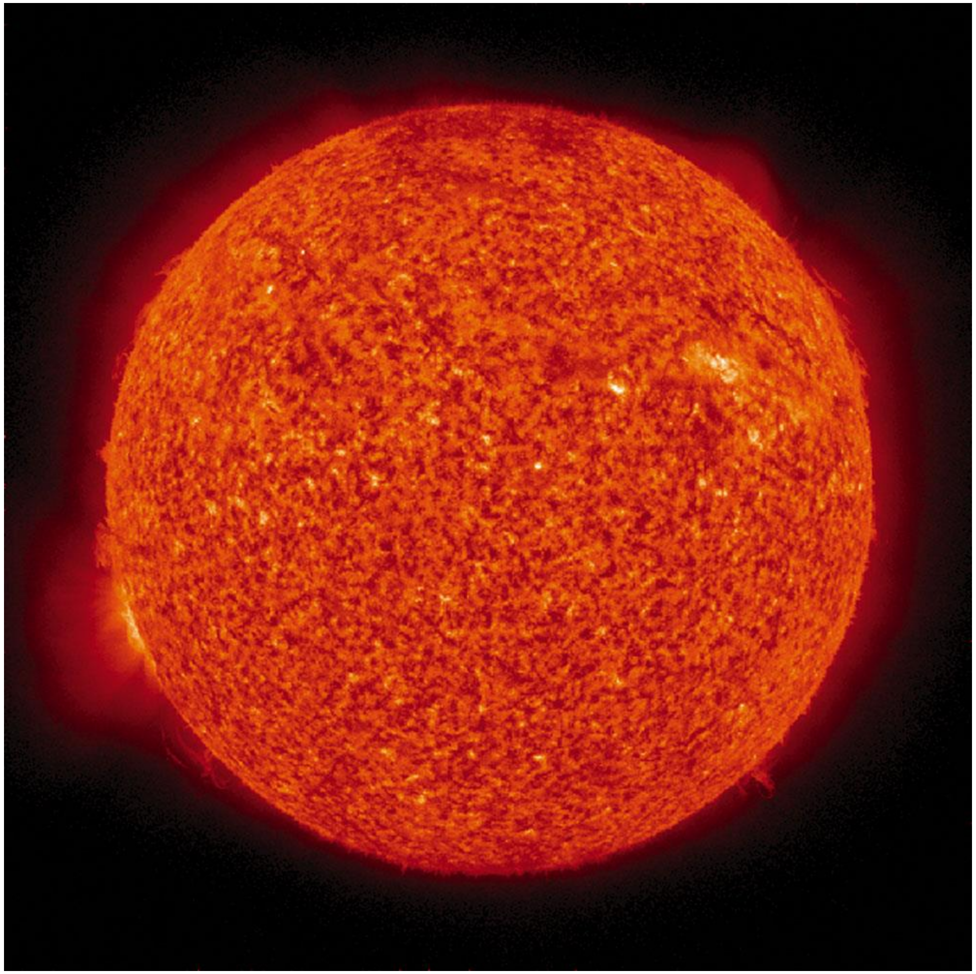
Δm = mass defect

ΔE = change in energy

c = speed of light

Because c^2 is so large, even small amounts of mass are converted to enormous amount of energy.

Nuclear Fusion and Stars



The Sun generates its energy by nuclear fusion of hydrogen nuclei into helium.

Nuclear Fission and Fusion

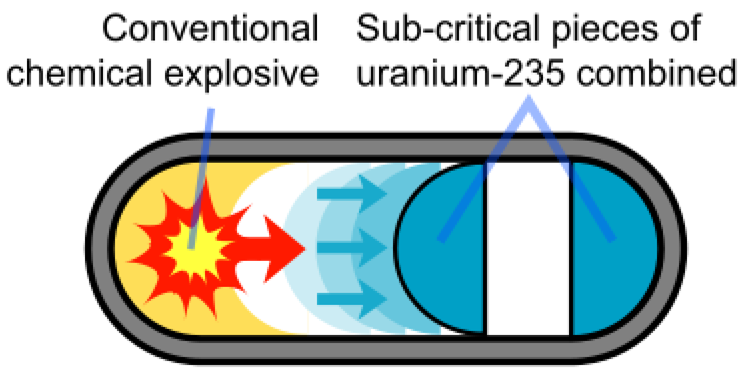
Fission: Splitting a heavy nucleus into two nuclei with smaller mass numbers.

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{142}_{56}Ba + {}^{91}_{36}Kr + 3\,{}^{1}_{0}n $$

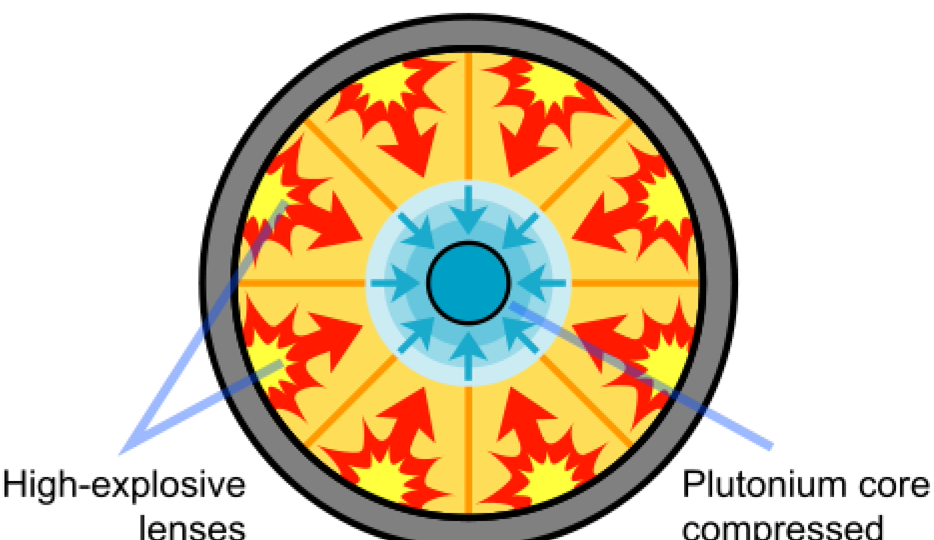
Fusion: Combining two light nuclei to form a heavier, more stable nucleus.

$$ {}^{3}_{2}He + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + {}^{0}_{1}e $$

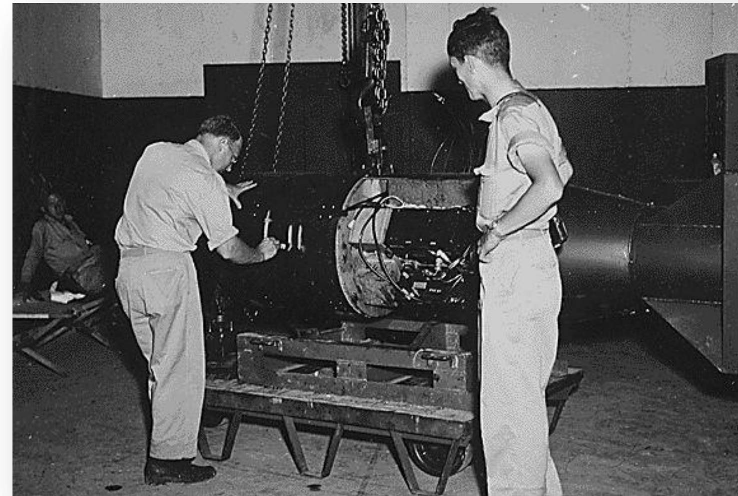
Fission Bomb Design



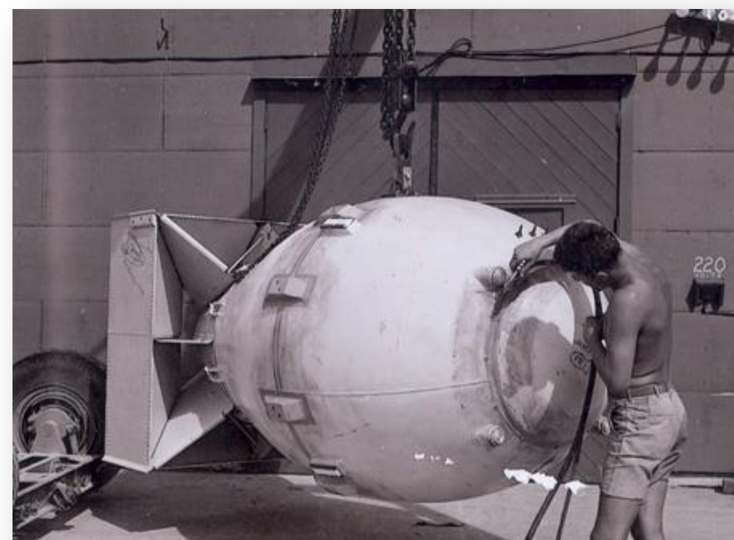
Gun-type assembly method



Implosion assembly method



Little Boy



Fat Man

Example 19.4 Radioactive Decay Kinetics

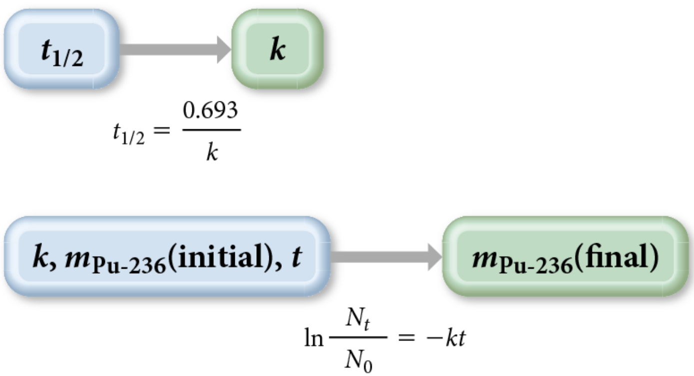
Plutonium-236 is an alpha emitter with a half-life of 2.86 years. If a sample initially contains 1.35 mg of Pu-236, what mass of Pu-236 is present after 5.00 years?

Sort

You are given the initial mass of Pu-236 in a sample and asked to find the mass after 5.00 years.

Given: $m_{\text{Pu-236}}(\text{initial}) = 1.35\text{ mg}$; $t = 5.00\text{ yr}$; $t_{1/2} = 2.86\text{ yr}$

Find: $m_{\text{Pu-236}}(\text{final})$



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

$$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{2.86\text{ yr}} = 0.24\underline{2}3/\text{yr}$$

$$\ln\frac{N_t}{N_0} = -kt$$

$$\frac{N_t}{N_0} = e^{-kt}$$

$$N_t = N_0 e^{-kt}$$

$$N_t = 1.35\text{ mg}\left[e^{-(0.24\underline{2}3/\text{yr})(5.00\text{ yr})}\right]$$

$$N_t = 0.402\text{ mg}$$