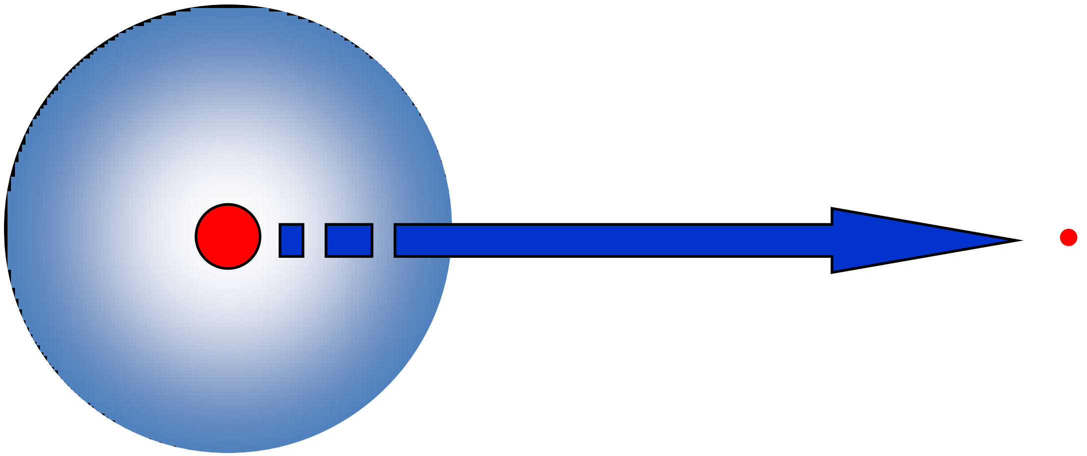
PS-21 First Spring Institute say 2012-2013: Teaching Physical Science

Radioactivity

What Is Radioactivity?

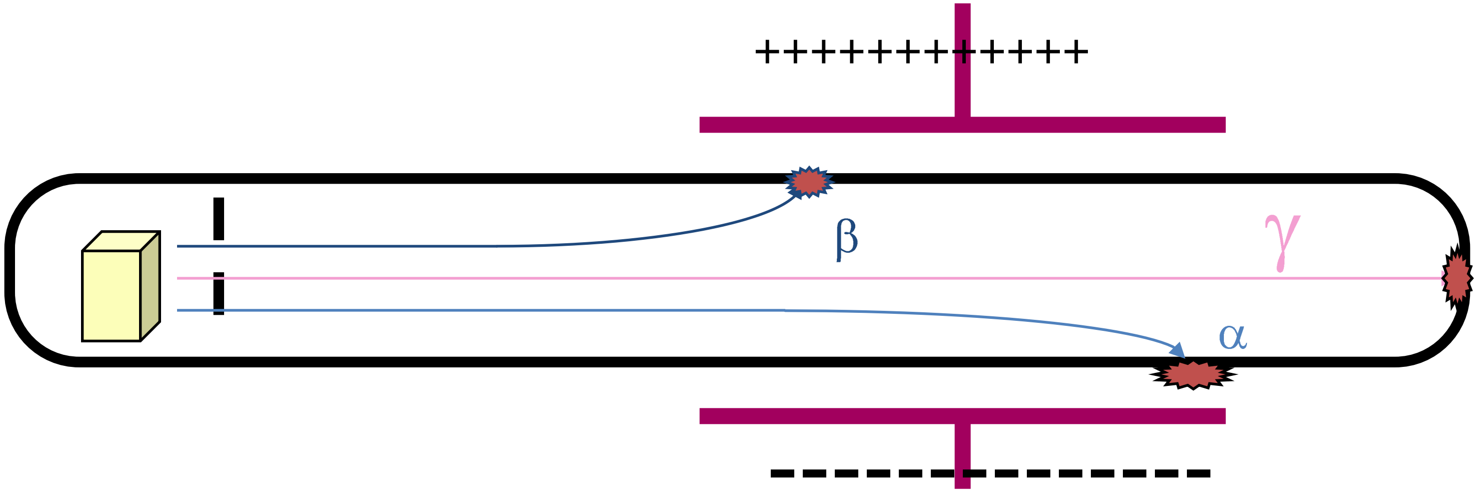
- Radioactivity is the release of tiny, high-energy particles or gamma rays from the nucleus of an atom



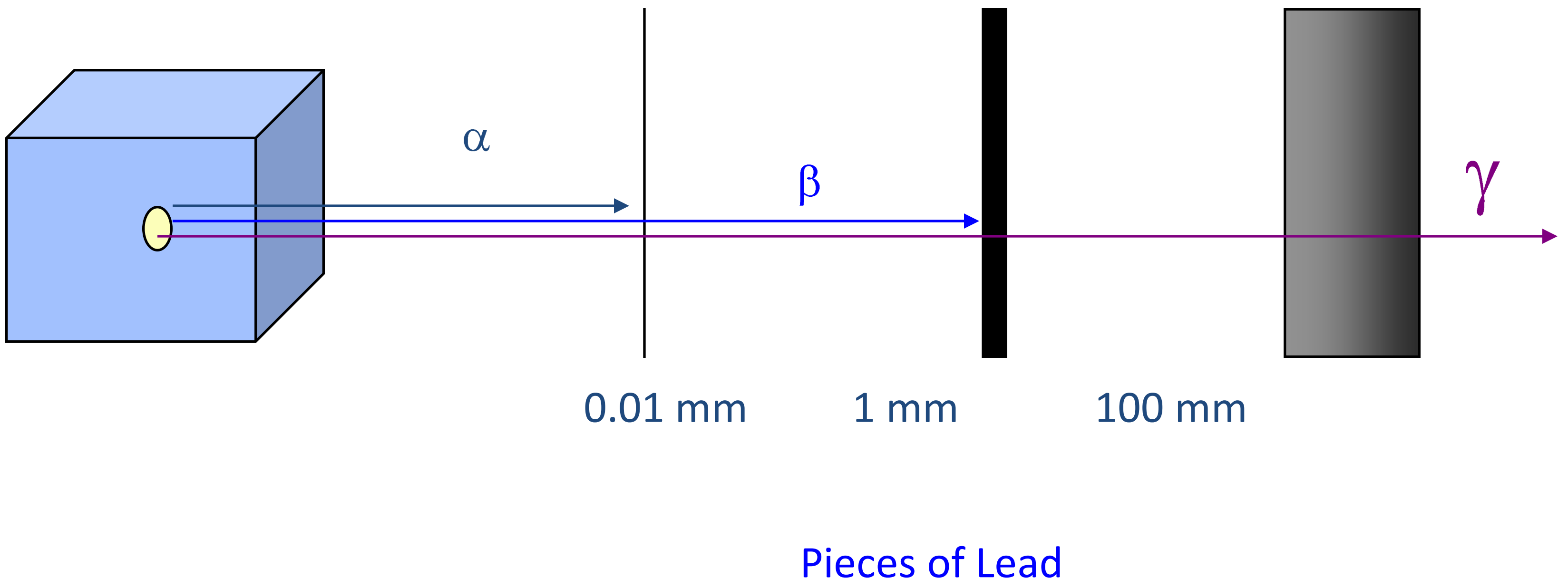
Types of Radioactive Decay

- Rutherford discovered three types of rays
  - **alpha** (α) **rays**
    - have a charge of +2 and a mass of 4 amu
    - helium nucleus
  - **beta** (β) **rays**
    - have a charge of −1 and small mass (<< 1 amu)
    - electron
  - **gamma** (γ) **rays**
    - electromagnetic radiation
- In addition, some unstable nuclei emit **positrons**
  - "a positively charged electron"
- Some unstable nuclei will undergo **electron capture**
  - a low energy electron is pulled into the nucleus

Rutherford’s Experiment



Penetrating Ability of Radioactive Rays



Penetrating Ability

Radiation	Range	Shielding
α	2.5-8 cm (air)	Paper (dead layers of skin for low energy)
β	15-1600 cm (air)	Low atomic number materials (Plexiglass)
γ	HVL air 1.3-13 m HVL lead 0.02 - 1.5 cm	Lead or high density material

HVL (half-value layer) – thickness of material required to reduce the original radiation intensity by 1/2

Facts About the Nucleus

- Every atom of an element has the same number of protons
  - **atomic number (*Z*)**
- Atoms of the same elements can have different numbers of neutrons
  - **isotopes**
  - different atomic masses
- Isotopes are identified by their **mass number (*A*)**
  - mass number = number of protons + neutrons

Facts About the Nucleus

- The number of neutrons is calculated by subtracting the atomic number from the mass number
- The nucleus of an isotope is called a **nuclide**
  - less than 10% of the known nuclides are non-radioactive, most are **radionuclides**
- Each nuclide is identified by a symbol
  - Element – Mass Number = X – A

$$\frac{\text{mass number}}{\text{atomic number}}\text{Element} = {}^{A}_{Z}X$$

Radioactivity

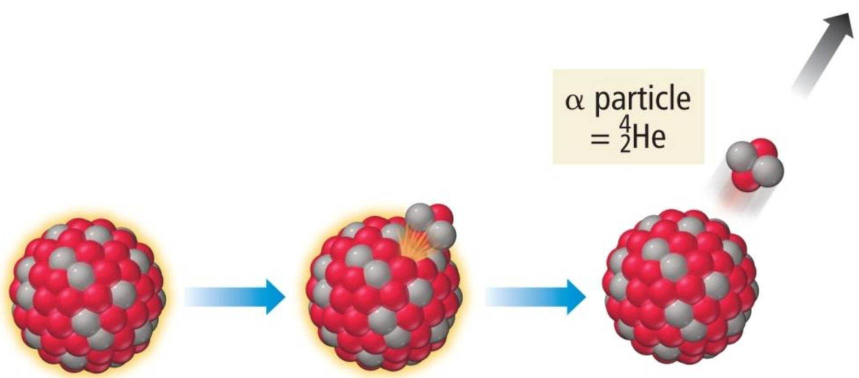
- Radioactive nuclei spontaneously decompose into smaller nuclei
  - radioactive decay
  - we say that radioactive nuclei are **unstable**
  - decomposing involves the nuclide emitting a particle and/or energy
- The **parent nuclide** is the nucleus that is undergoing radioactive decay
- The **daughter nuclide** is the new nucleus that is made
- All nuclides with 84 or more protons are radioactive

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^+	${}^{0}_{+1}\beta$ ${}^{0}_{+1}e$

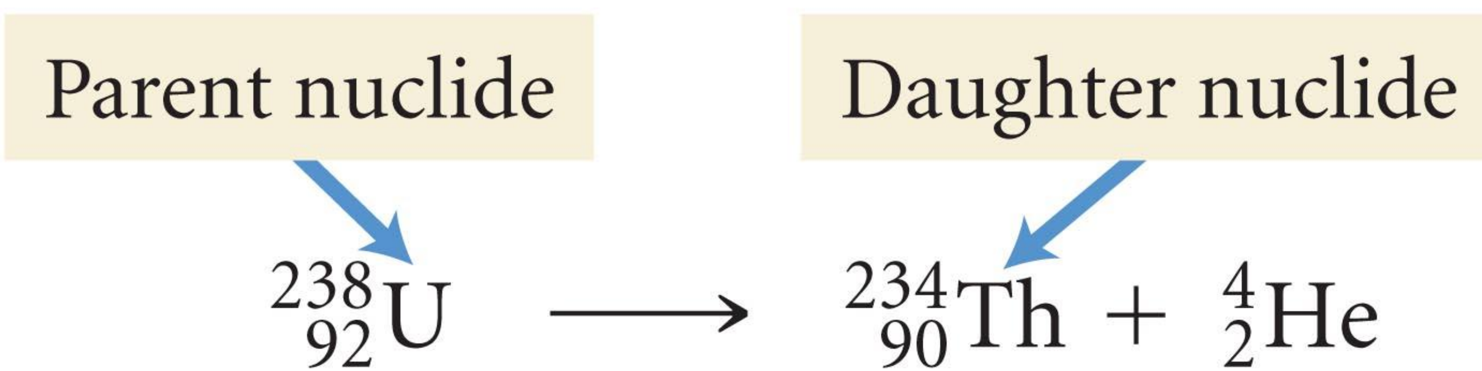
Transmutation

- Rutherford discovered that during the radioactive process, atoms of one element are changed into atoms of a different element – **transmutation**
  - ✓ showing that statement 3 of Dalton's Atomic Theory is not valid all the time, only for ***chemical*** reactions
- For one element to change into another, the **number of protons in the nucleus must change!**



Nuclear Equations

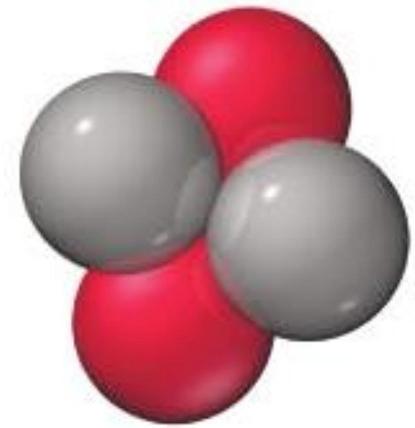
- In the nuclear equation, mass numbers and atomic numbers are conserved
- We can use this fact to determine the identity of a daughter nuclide if we know the parent and mode of decay



Alpha Emission

- An α particle contains 2 protons and 2 neutrons
  - ✓helium nucleus
- Most ionizing, but least penetrating of the types of radioactivity
- Loss of an alpha particle means
  - ✓atomic number decreases by 2
  - ✓mass number decreases by 4

$^{4}_{2}\alpha$ $^{4}_{2}\mathrm{He}$



$$^{222}_{88}\mathrm{Ra} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{218}_{86}\mathrm{Rn}$$

Beta Emission

- A β particle is an electron
  - moving very faster
  - produced from the nucleus

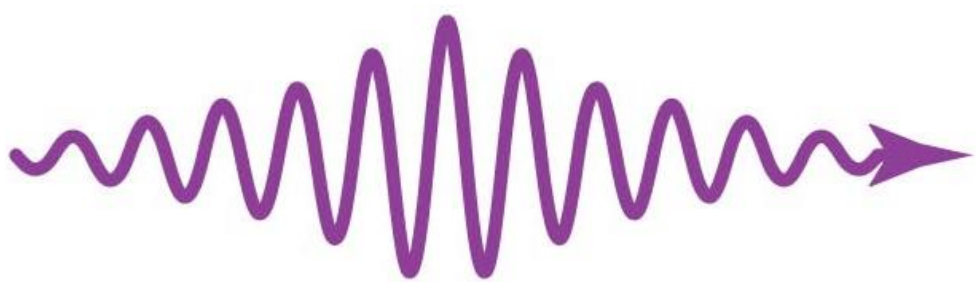
$$^{0}_{-1}\beta \quad ^{0}_{-1}\mathrm{e}$$

- About 10 times more penetrating than α, but only about half the ionizing ability
- When an atom loses a β particle its
  - atomic number increases by 1
  - mass number remains the same
- In beta decay, a neutron changes into a proton

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

Gamma Emission $^{0}_{0}\gamma$

- Gamma (γ) rays are high energy photons of light
- No change in the composition of the nucleus
  - same atomic number and mass number
- Least ionizing, but most penetrating
- Generally occurs after the nucleus undergoes some other type of decay and the remaining particles rearrange



Positron Emission

- Positron has a charge of +1 $^{0}_{+1}\beta$ $^{0}_{+1}e$ 
  - anti-electron
- Similar to beta particles in their ionizing and penetrating ability
- When an atom loses a positron from the nucleus, its
  - mass number remains the same
  - atomic number decreases by 1
- Positrons result from a proton changing into a neutron

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

Electron Capture $^{0}_{-1}e$

- Occurs when an inner orbital electron is pulled into the nucleus
- No particle emission, but atom changes
  - same result as positron emission
- Proton combines with the electron to make a neutron
  - mass number stays the same
  - atomic number decreases by one

$$^{92}_{44}Ru + ^{0}_{-1}e \rightarrow ^{92}_{43}Tc$$

$$^{92}_{44}Ru \rightarrow ^{92}_{43}Tc$$

Particle Changes

- Beta Emission – neutron changing into a proton

$$ {}_{0}^{1}n \rightarrow {}_{1}^{1}p + {}_{-1}^{0}\beta $$

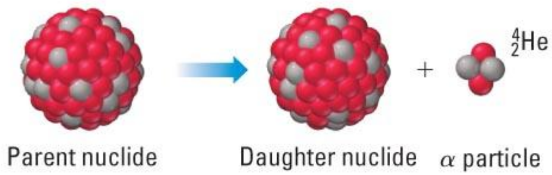
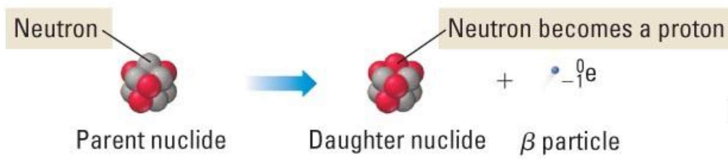
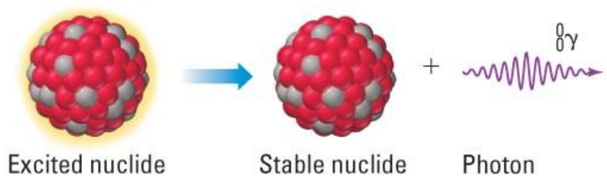
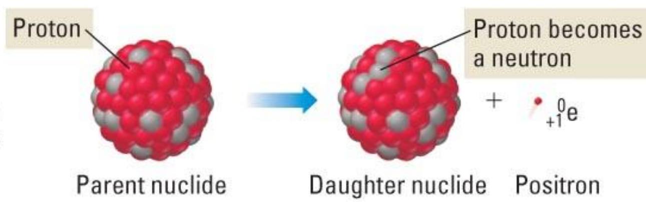
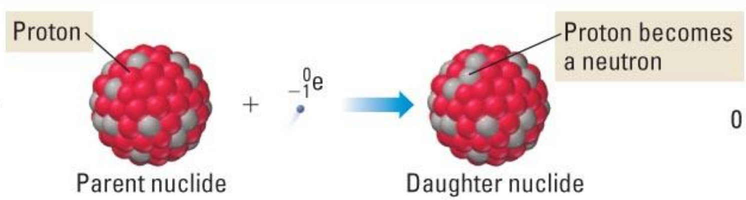
- Positron Emission – proton changing into a neutron

$$ {}_{1}^{1}p \rightarrow {}_{0}^{1}n + {}_{+1}^{0}\beta $$

- Electron Capture – proton changing into a neutron

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

TABLE 19.1 Modes of Radioactive Decay

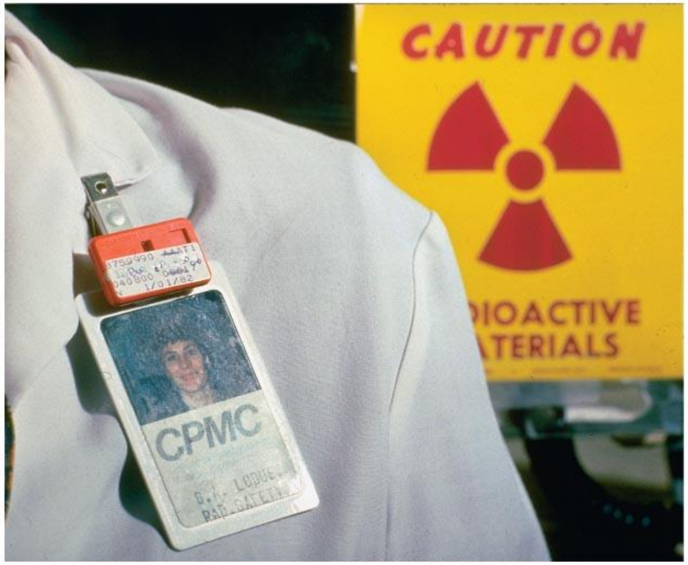
Decay Mode	Process	Change in: *A*	*Z*	*N/Z**	Example
α		−4	−2	Increase	$^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$
β		0	+1	Decrease	$^{228}_{88}Ra \longrightarrow ^{228}_{89}Ac + ^{0}_{-1}e$
γ		0	0	None	$^{234}_{90}Th \longrightarrow ^{234}_{90}Th + ^{0}_{0}\gamma$
Positron emission		0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

Detecting Radioactivity

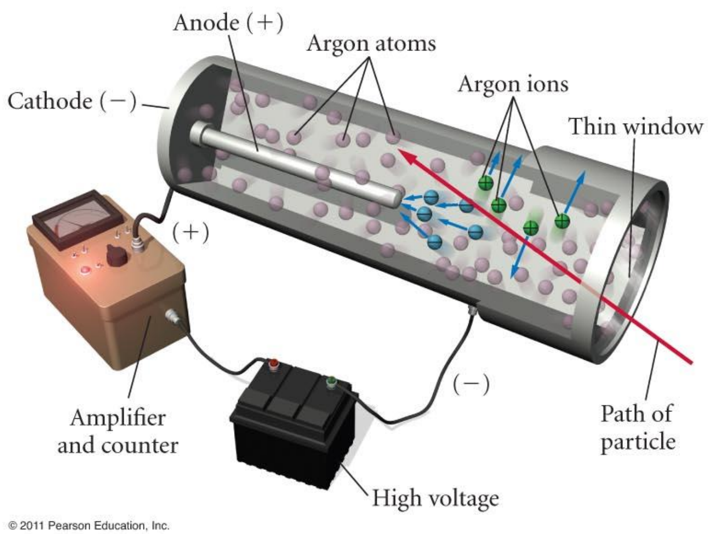
To detect something, you need to identify what it does

- Radioactive rays can expose light-protected photographic film
- We may use photographic film to detect the presence of radioactive rays – ***film badge dosimeters***



Detecting Radioactivity

- Radioactive rays cause air to become ionized
- A ***Geiger-Müller counter*** works by counting electrons generated when Ar gas atoms are ionized by radioactive rays

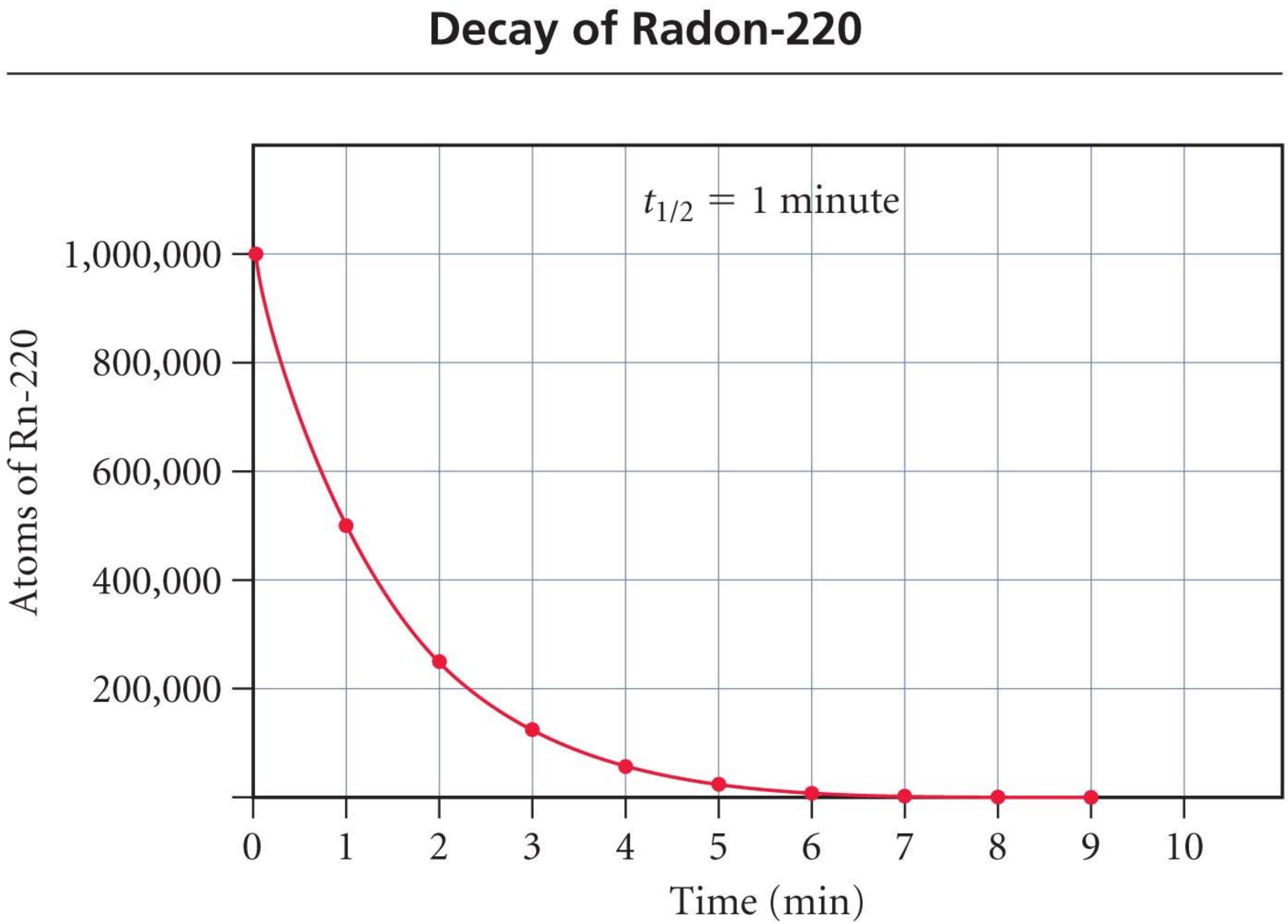


Kinetics of Radioactive Decay

- Rate = kN
  - N = number of radioactive nuclei
- $t_{1/2} = 0.693/k$
- the shorter the half-life, the more nuclei decay every second – we say the sample is hotter

$$\ln \frac{N_t}{N_0} = -kt = \ln \frac{\text{rate}_t}{\text{rate}_0}$$

Pattern for Radioactive Decay



Half-Lives of Various Nuclides

Nuclide	Half-Life	Type of Decay
Th–232	1.4×10^{10} yr	alpha
U–238	4.5×10^{9} yr	alpha
C–14	5730 yr	beta
Rn–220	55.6 sec	alpha
Th–219	1.05×10^{-6} sec	alpha

Biological Effects of Radiation

- Radiation has high energy, energy enough to knock electrons from molecules and break bonds
  - **ionizing radiation**
- Energy transferred to cells can damage biological molecules and cause malfunction of the cell

Acute Effects of Radiation

- High levels of radiation over a short period of time kill large numbers of cells
  - from a nuclear blast or exposed reactor core
- Causes weakened immune system and lower ability to absorb nutrients from food
  - may result in death, usually from infection

Chronic Effects

- Low doses of radiation over a period of time show an increased risk for the development of cancer
  - radiation damages DNA that may not get repaired properly
- Low doses over time may damage reproductive organs, which may lead to sterilization
- Damage to reproductive cells may lead to genetic defects in offspring

Measuring Radiation Exposure

- The **curie (Ci)** is an exposure of 3.7×10^{10} events per second
  - no matter the kind of radiation
- The **gray (Gy)** measures the amount of energy absorbed by body tissue from radiation
  - 1 Gy = 1 J/kg body tissue
- The **rad** also measures the amount of energy absorbed by body tissue from radiation
  - 1 rad = 0.01 Gy
- A correction factor is used to account for a number of factors that affect the result of the exposure – this biological effectiveness factor is the RBE, and the result is the dose in **rems**
  - rads x RBE = rems
  - rem = roentgen equivalent man

Factors that Determine the Biological Effects of Radiation

1. The more energy the radiation has, the larger its effect can be
2. The better the ionizing radiation penetrates human tissue, the deeper effect it can have
   – Gamma >> Beta > Alpha
3. The more ionizing the radiation, the larger the effect of the radiation
   – Alpha > Beta > Gamma
4. The radioactive half-life of the radionuclide
5. The biological half-life of the element
6. The physical state of the radioactive material

TABLE 19.4 Exposure by Source for Persons Living in the United States

Source	Dose
Natural Radiation	
A 5-hour jet airplane ride	2.5 mrem/trip (0.5 mrem/hr at 39,000 feet) (whole body dose)
Cosmic radiation from outer space	27 mrem/yr (whole body dose)
Terrestrial radiation	28 mrem/yr (whole body dose)
Natural radionuclides in the body	35 mrem/yr (whole body dose)
Radon gas	200 mrem/yr (lung dose)
Diagnostic Medical Procedures	
Chest X-ray	8 mrem (whole body dose)
Dental X-rays (panoramic)	30 mrem (skin dose)
Dental X-rays (two bitewings)	80 mrem (skin dose)
Mammogram	138 mrem per image
Barium enema (X-ray portion only)	406 mrem (bone marrow dose)
Upper gastrointestinal tract test	244 mrem (X-ray portion only) (bone marrow dose)
Thallium heart scan	500 mrem (whole body dose)
Consumer Products	
Building materials	3.5 mrem/year (whole body dose)
Luminous watches (H-3 and Pm-147)	0.04–0.1 mrem/year (whole body dose)
Tobacco products (to smokers of 30 cigarettes per day)	16,000 mrem/year (bronchial epithelial dose)

Source: Department of Health and Human Services, National Institutes of Health.

Biological Effects of Radiation

- The amount of danger to humans of radiation is measured in the unit **rems**

Dose (rems)	Probable Outcome
20-100	decreased white blood cell count; possible increased cancer risk
100-400	radiation sickness; increased cancer risk
500	Death of ½ of exposed population within 30 days of exposure

Exposures

- Three Mile Island – 20 Ci released; no one exposed to >100 rem
- Chernobyl – 50×10^6 – 100×10^6 Ci; firefighters received >100 rem