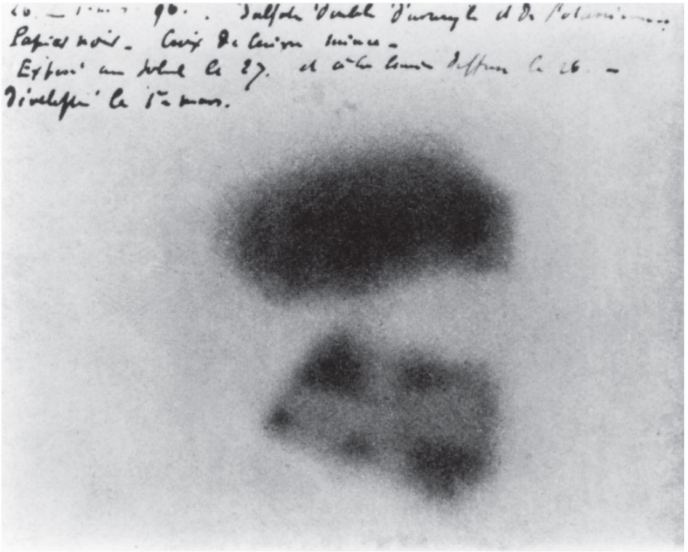
The Discovery of Radioactivity

- Antoine-Henri Becquerel designed an experiment to determine if phosphorescent minerals also gave off X-rays



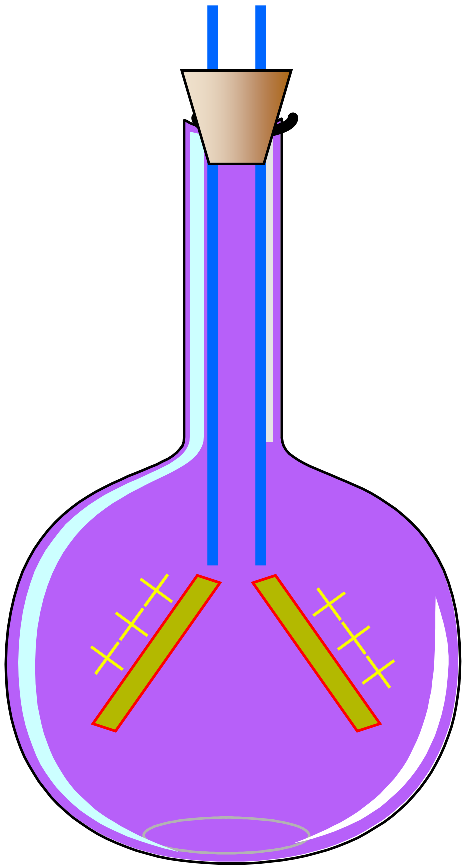
The Discovery of Radioactivity

- Becquerel discovered that certain minerals were constantly producing penetrating energy rays he called ***uranic rays***
  - ✓ like X-rays
  - ✓ but not related to fluorescence
- Becquerel determined that
  - ✓ all the minerals that produced these rays contained uranium
  - ✓ the rays were produced even though the mineral was not exposed to outside energy
- *Energy apparently being produced from nothing??*

The Curies

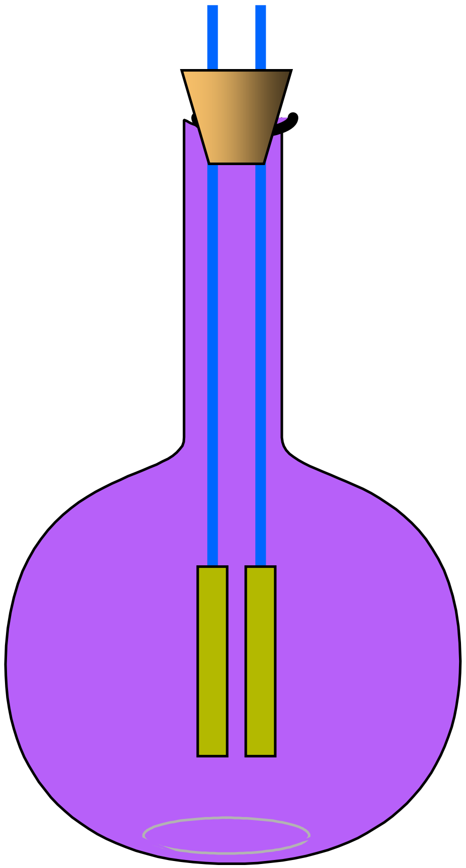
- Marie Curie used electroscope to detect uranic rays in samples
- Discovered new elements by detecting their rays
  - ✓ **radium** named for its green phosphorescence
  - ✓ **polonium** named for her homeland
- Since these rays were no longer just a property of uranium, she renamed it **radioactivity**

Electroscope



When charged, the metal foils spread apart due to like charge repulsion

When exposed to ionizing radiation, the radiation knocks electrons off the air molecules, which jump onto the foils and discharge them, causing them to drop down.



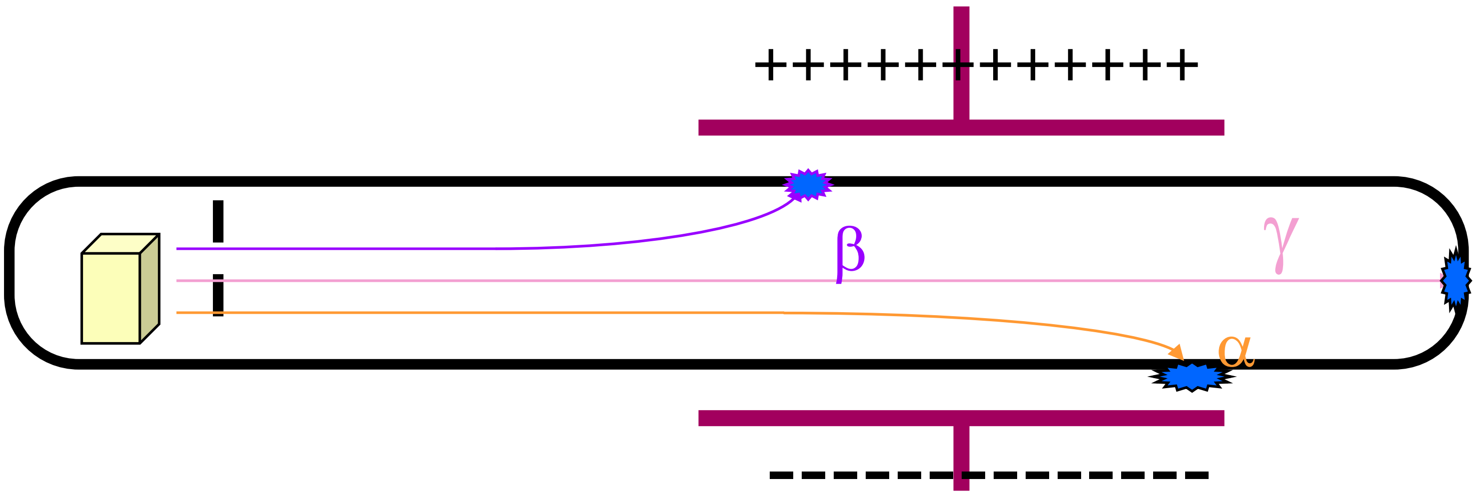
Other Properties of Radioactivity

- radioactive rays can **ionize** matter
  - ✓cause uncharged matter to become charged
  - ✓basis of Geiger Counter and electroscope
- radioactive rays have high energy
- radioactive rays can penetrate matter
- radioactive rays cause phosphorescent chemicals to glow
  - ✓basis of scintillation counter

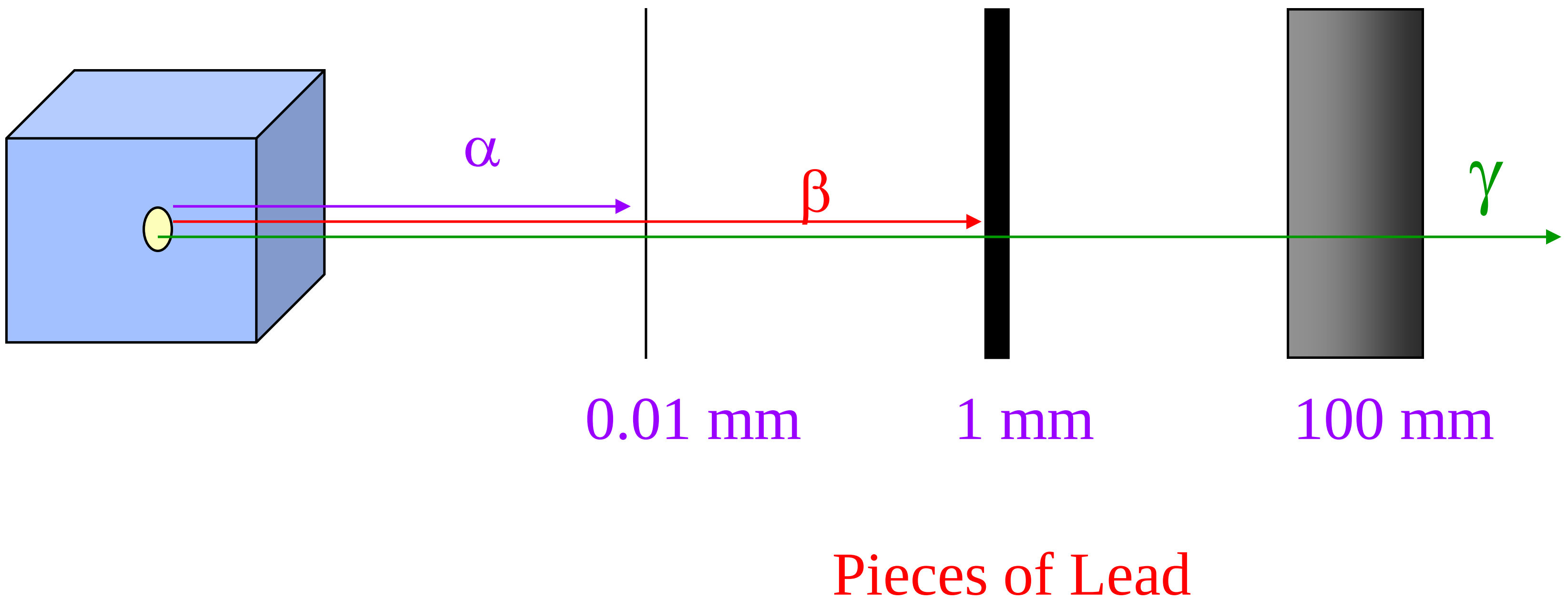
Types of Radioactive Rays

- Rutherford discovered there were three types of radioactivity
- **alpha rays** (α)
  - ✓have a charge of +2 c.u. and a mass of 4 amu
  - ✓what we now know to be helium nucleus
- **beta rays** (β)
  - ✓have a charge of -1 c.u. and negligible mass
  - ✓electron-like
- **gamma rays** (γ)
  - ✓form of light energy (not particle like α and β)

Rutherford's Experiment



Penetrating Ability of Radioactive Rays



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

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

Radioactivity

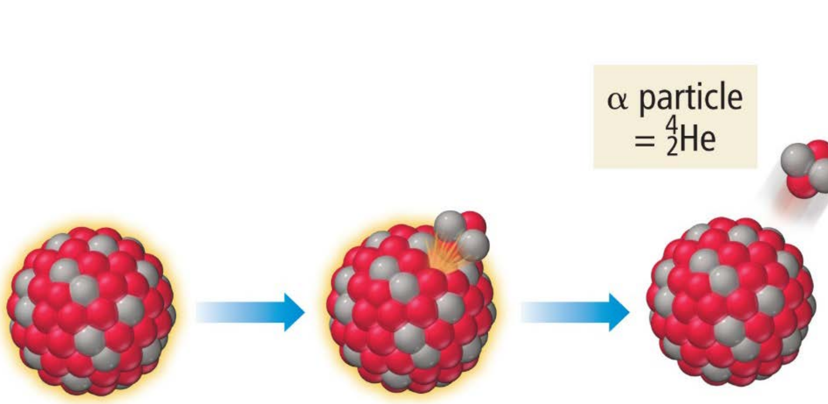
- Radioactive nuclei spontaneously decompose into smaller nuclei
  - ✓ Radioactive decay
  - ✓ We say that radioactive nuclei are **unstable**
- The parent nuclide is the nucleus that is undergoing radioactive decay, the daughter nuclide is the new nucleus that is made
- Decomposing involves the nuclide emitting a particle and/or energy
- 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^+	${}^{0}_{+1}\beta$ ${}^{0}_{+1}e$

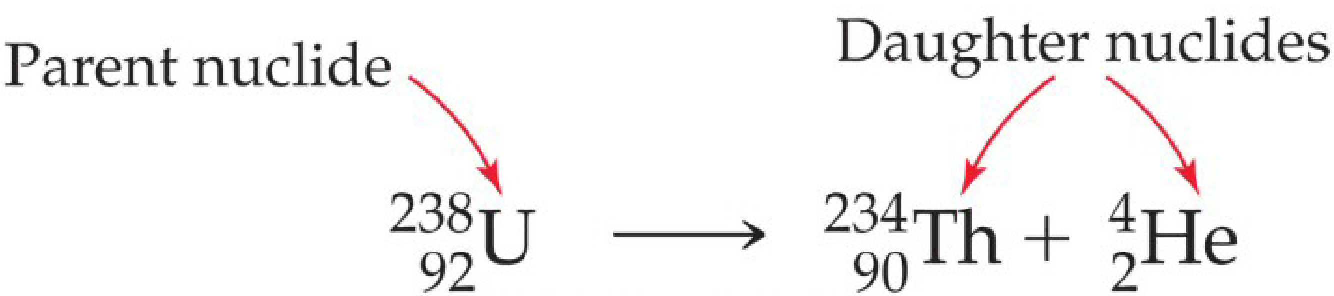
Transmutation

- Rutherford discovered that during the radioactive process, atoms of one element are changed into atoms of a different element - **transmutation**
  - ✓ Dalton's Atomic Theory statement 3 bites the dust
- **in order for one element to change into another, the number of protons in the nucleus must change**



Nuclear Equations

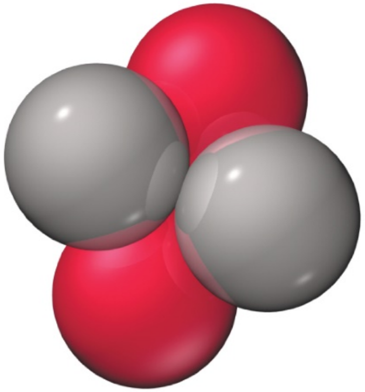
- we describe nuclear processes with nuclear equations
- use the symbol of the nuclide to represent the nucleus
- atomic numbers and mass numbers are conserved
    - ✓ use this fact to predict the daughter nuclide if you know parent and emitted particle



Alpha Emission

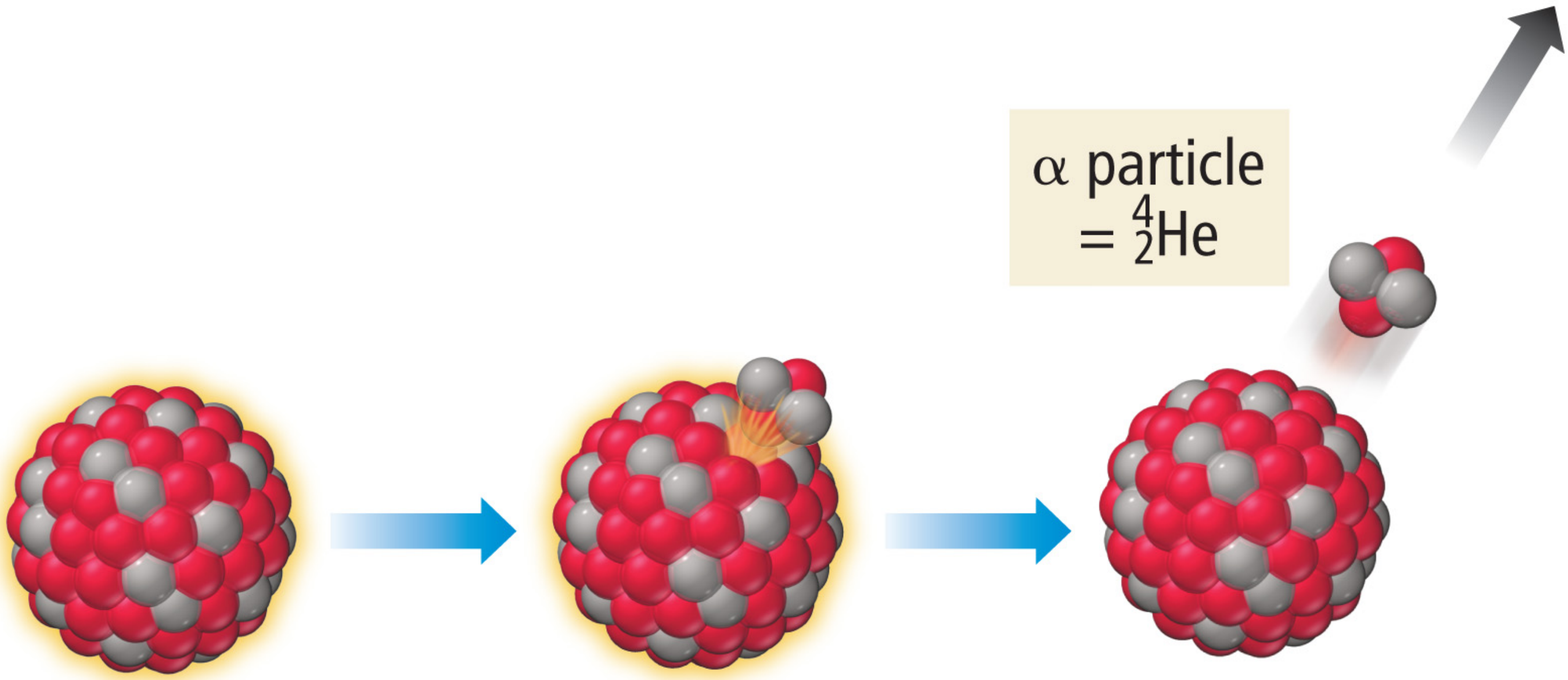
- an α particle contains 2 protons and 2 neutrons
  - ✓helium nucleus
- most ionizing, but least penetrating
- loss of an alpha particle means
  - ✓atomic number decreases by 2
  - ✓mass number decreases by 4

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



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

Alpha Decay



Beta Emission

- a β particle is like an electron
  - ✓moving much faster
  - ✓produced from the nucleus

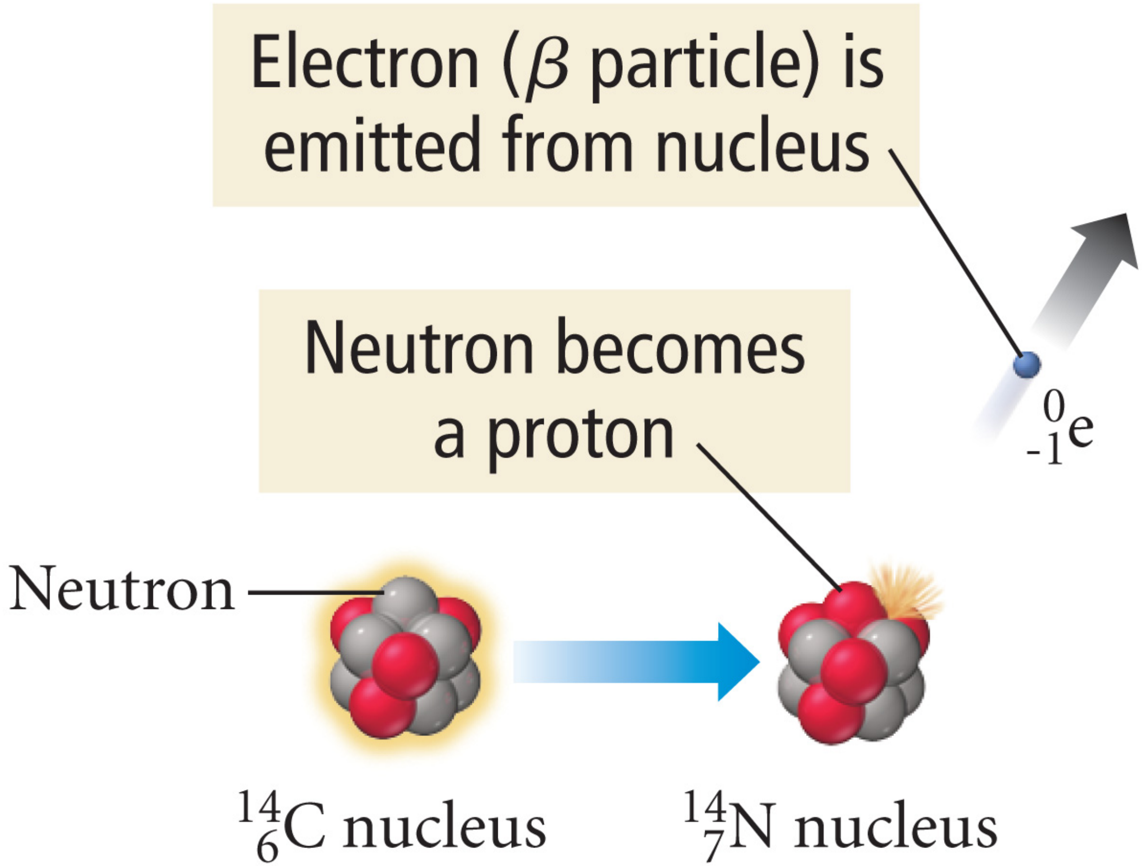
$$ {}^{0}_{-1}\beta \quad {}^{0}_{-1}e $$

- 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

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

Beta Decay



Electron (β particle) is emitted from nucleus
Neutron becomes a proton
Neutron
$^{0}_{-1}e$
$^{14}_{6}C$ nucleus
$^{14}_{7}N$ nucleus

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

- gamma (γ) rays are high energy photons of light
- no loss of particles from the nucleus
- 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 c.u. and negligible mass
  - ✓anti-electron

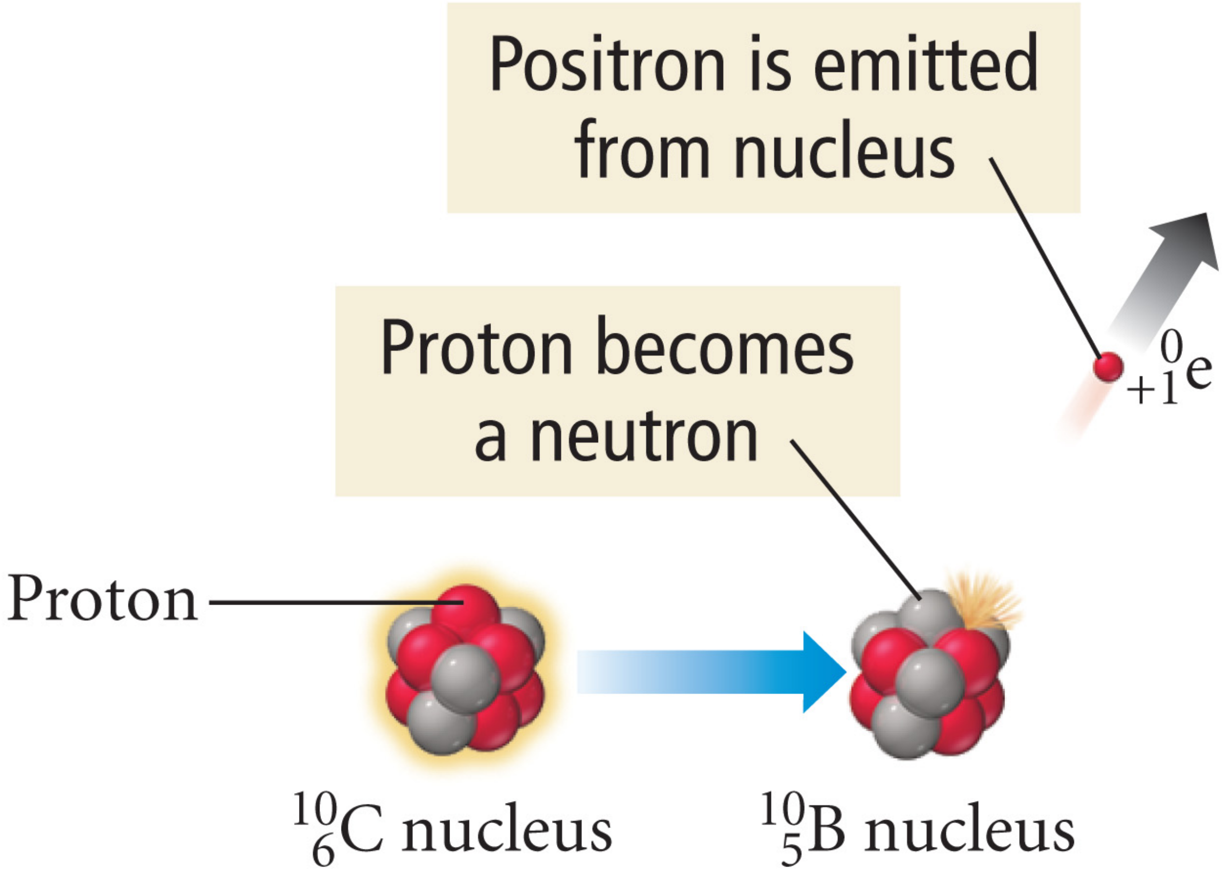
$$ {}^{0}_{+1}\beta \quad {}^{0}_{+1}e $$

- when an atom loses a positron from the nucleus, its
  - ✓mass number remains the same
  - ✓atomic number decreases by 1

- positrons appear to result from a proton changing into a neutron

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

Positron Emission



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

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

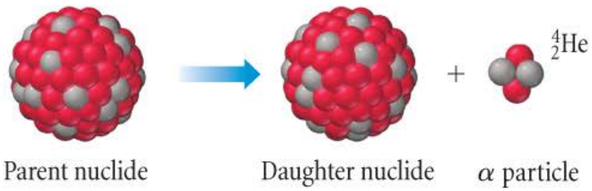
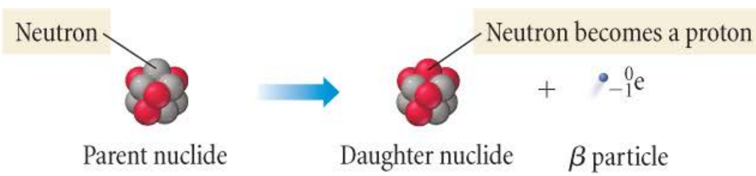
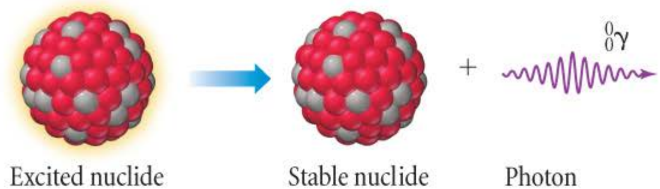
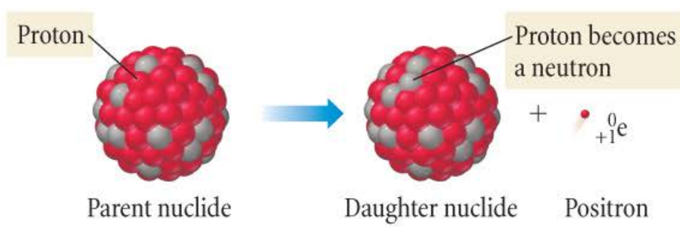
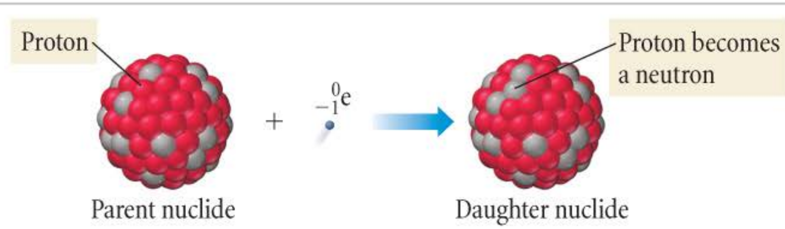
- Positron Emission – proton changing into a neutron

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

- Electron Capture – proton changing into a neutron

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

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

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

$$x + 4 = 232;\ x = 228$$

$$^{232}_{90}\mathrm{Th} \longrightarrow \underbrace{\overbrace{^{x}_{y}? + {}^{4}_{2}\mathrm{He}}}$$

$$y + 2 = 90;\ y = 88$$

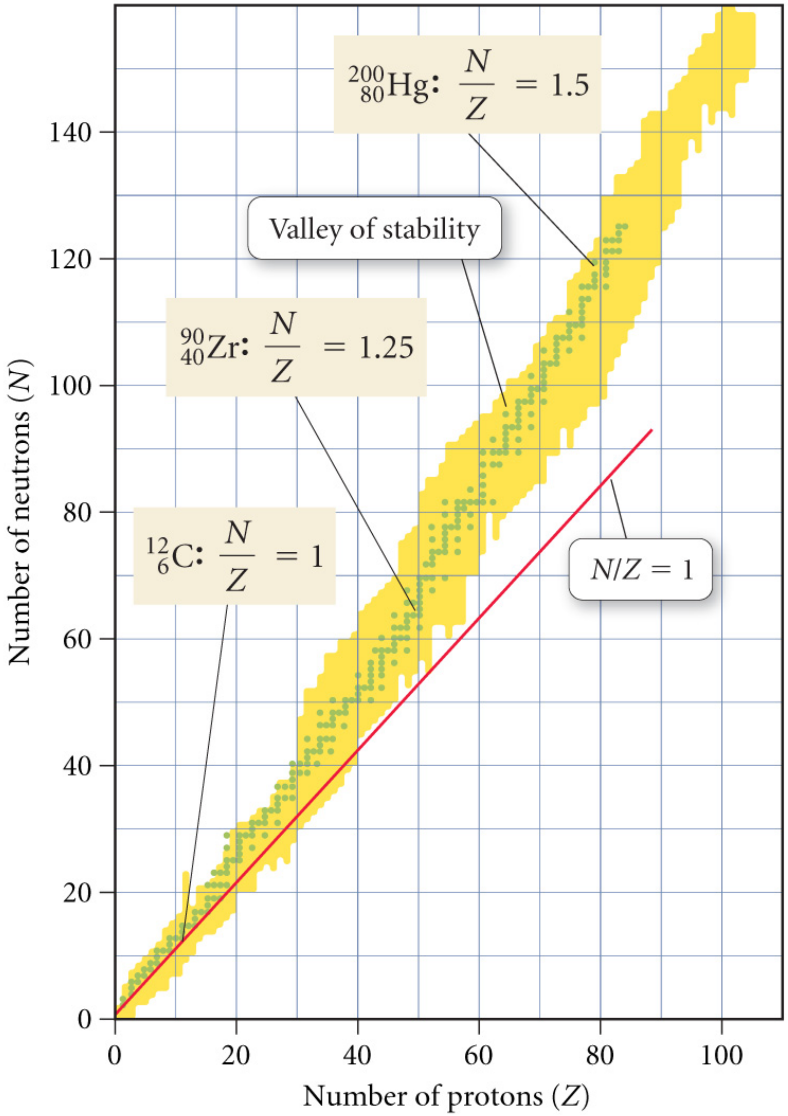
What Causes Nuclei to Break Down?

- the particles in the nucleus are held together by a very strong attractive force only found in the nucleus called the **strong force**
  - ✓acts only over very short distances
- the neutrons play an important role in stabilizing the nucleus, as they add to the strong force, but don’t repel each other like the protons do

N/Z Ratio

- the ratio of neutrons : protons is an important measure of the stability of the nucleus
- if the N/Z ratio is too high – neutrons are converted to protons via β decay
- if the N/Z ratio is too low – protons are converted to neutrons via positron emission or electron capture
  - ✓or via α decay – though not as efficient

Valley of Stability



for Z = 1 ⇒ 20,
stable N/Z ≈ 1

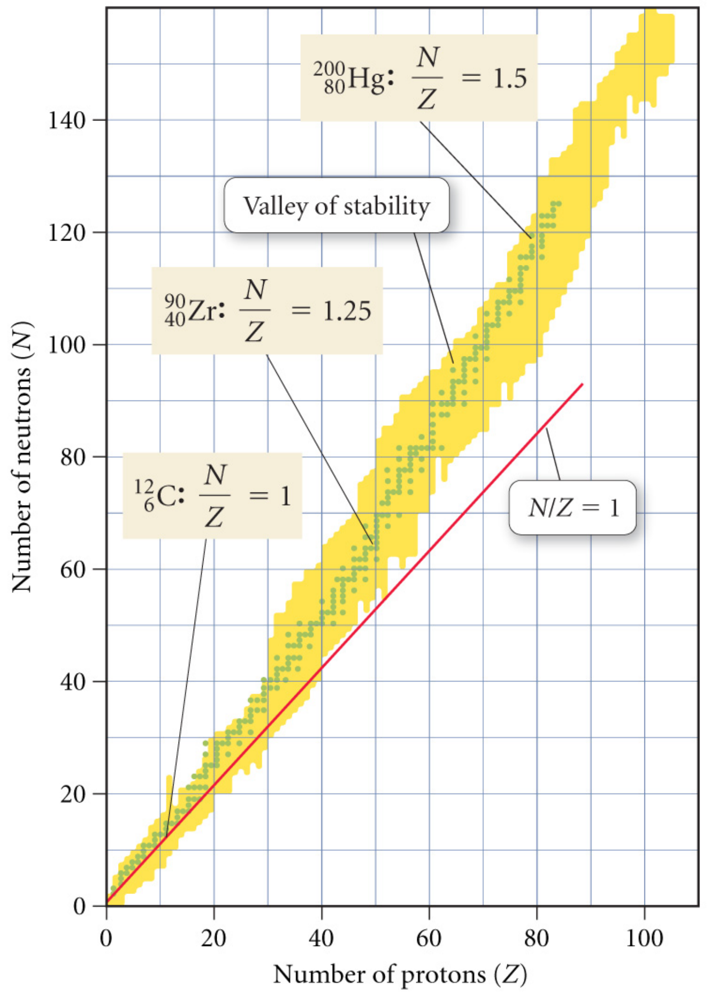
for Z = 20 ⇒ 40,
stable N/Z approaches 1.25

for Z = 40 ⇒ 80,
stable N/Z approaches 1.5

for Z > 83,
there are no stable nuclei

Ex 19.3b Determine the kind of radioactive decay that Mg-22 undergoes

- Mg-22
  - ✓ Z = 12
  - ✓ N = 22 – 12 = 10
- N/Z = 10/12 = 0.83
- from Z = 1 ⇒ 20, stable nuclei have N/Z ≈ 1
- since Mg-22 N/Z is low, it should convert p^+ into n^0, therefore it will undergo **positron emission or electron capture**



Magic Numbers

- besides the N/Z ratio, the actual numbers of protons and neutrons effects stability
- most stable nuclei have even numbers of protons and neutrons
- only a few have odd numbers of protons and neutrons
- if the total number of nucleons adds to a magic number, the nucleus is more stable
  - ✓ same idea as the electrons in the noble gas resulting in a more stable electron configuration
  - ✓ most stable when N or Z = 2, 8, 20, 28, 50, 82; or N = 126

TABLE 19.2 Number of Stable Nuclides with Even and Odd Numbers of Nucleons

Z	*N*	Number of Nuclides
Even	Even	157
Even	Odd	53
Odd	Even	50
Odd	Odd	5

Decay Series

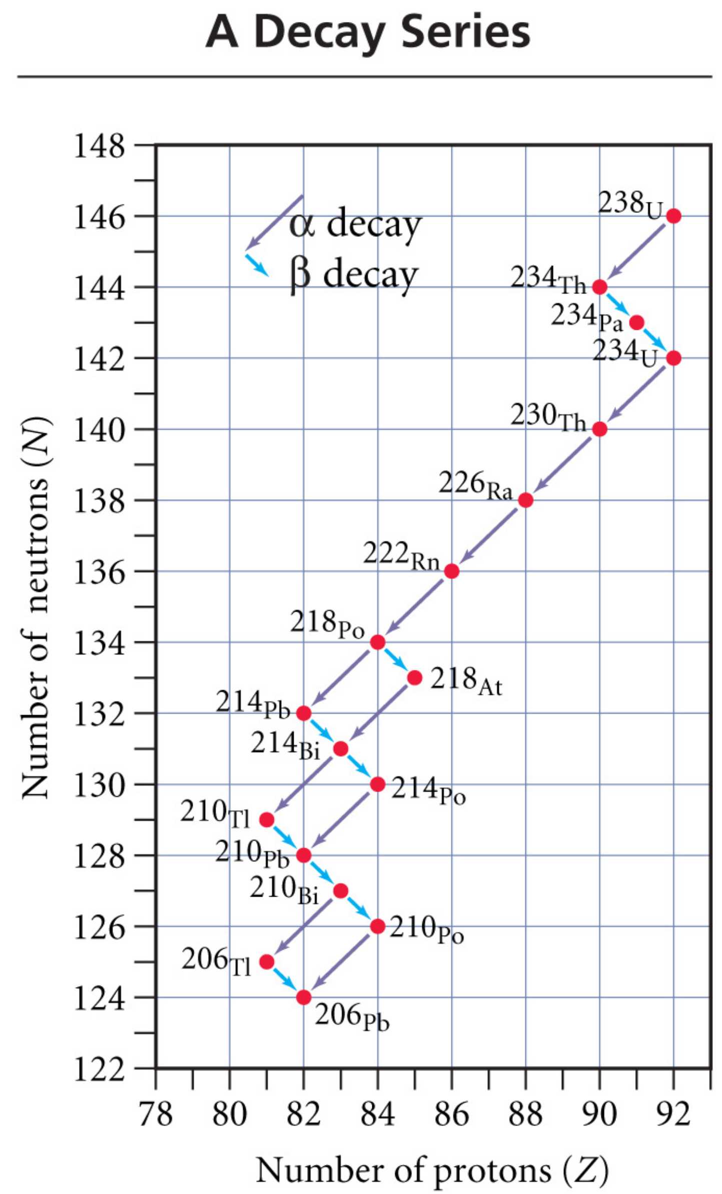
- in nature, often one radioactive **nuclide** changes in another radioactive nuclide
  - ✓ daughter nuclide is also radioactive
- all of the radioactive nuclides that are produced one after the other until a stable nuclide is made is called a **decay series**
- to determine the stable nuclide at the end of the series without writing it all out
  1. count the number of α and β decays
  2. from the mass no. subtract 4 for each α decay
  3. from the atomic no. subtract 2 for each α decay and add 1 for each β

U-238 Decay Series

α
β
β
α
α
α
α

β	or	α
α		β
β		α
α		β
β		β
β		α
α		β

or other combinations

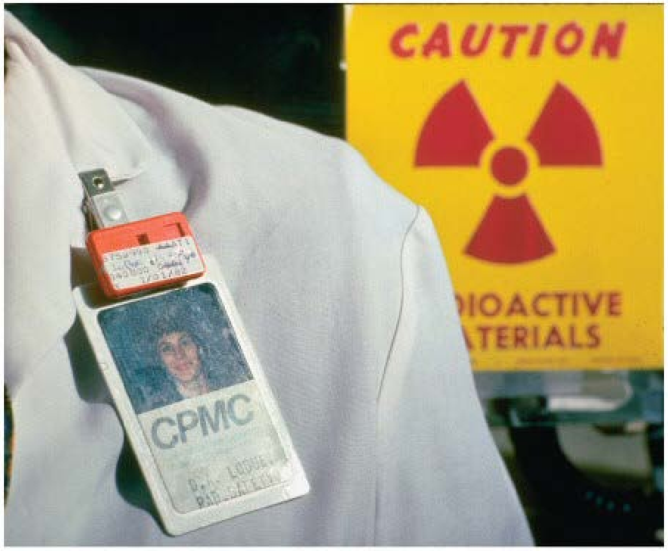


Detecting Radioactivity

To detect something, you need to identify what it does

- Radioactive rays can expose light-protected photographic film

  Use photographic film to detect its presence – ***film badges***

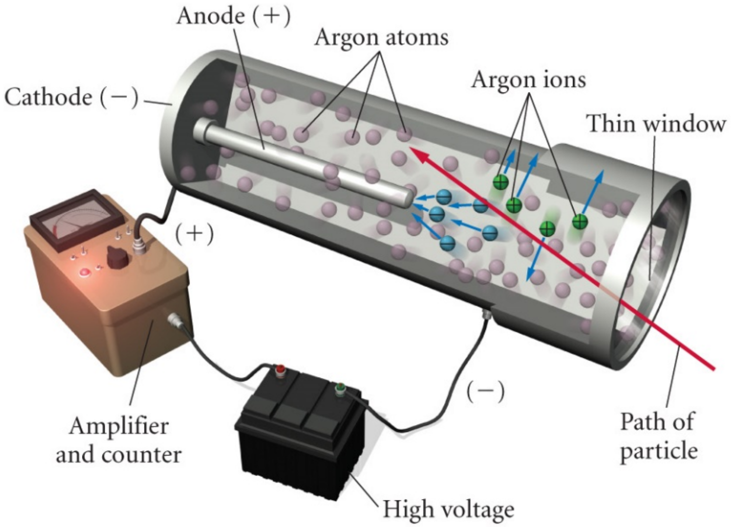


Detecting Radioactivity

- Radioactive rays cause air to become ionized

  An ***electroscope*** detects radiation by its ability to penetrate the flask and ionize the air inside

  A Geiger-Müller Counter works by counting electrons generated when Ar gas atoms are ionized by radioactive rays



Detecting Radioactivity

- Radioactive rays cause certain chemicals to give off a flash of light when they strike the chemical

  A ***scintillation counter*** is able to count the number of flashes per minute

Natural Radioactivity

- there are small amounts of radioactive minerals in the air, ground, and water
- even in the food you eat!
- the radiation you are exposed to from natural sources is called **background radiation**

Rate of Radioactivity

- it was discovered that the rate of change in the amount of radioactivity was constant and 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**
- **rate of change not affected by temperature**
  - ✓means that radioactivity is not a chemical reaction!

Kinetics of Radioactive Decay

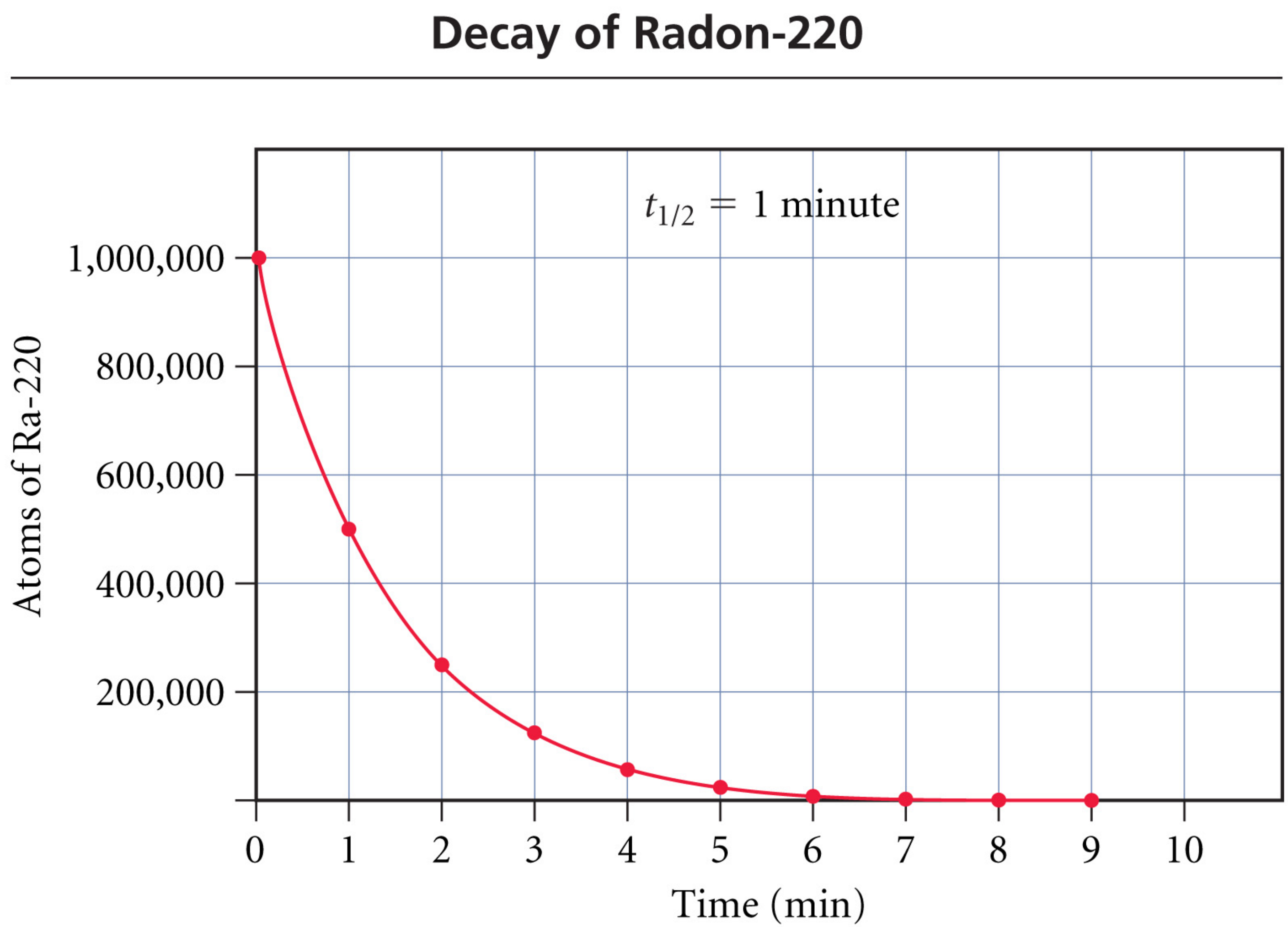
- Rate = kN
  - ✓N = number of radioactive nuclei
- $t_{1/2} = 0.693/k$
- the shorter the half-life, the more nuclei decay every second – we say the sample is hotter

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

Half-Lives of Various Nuclides

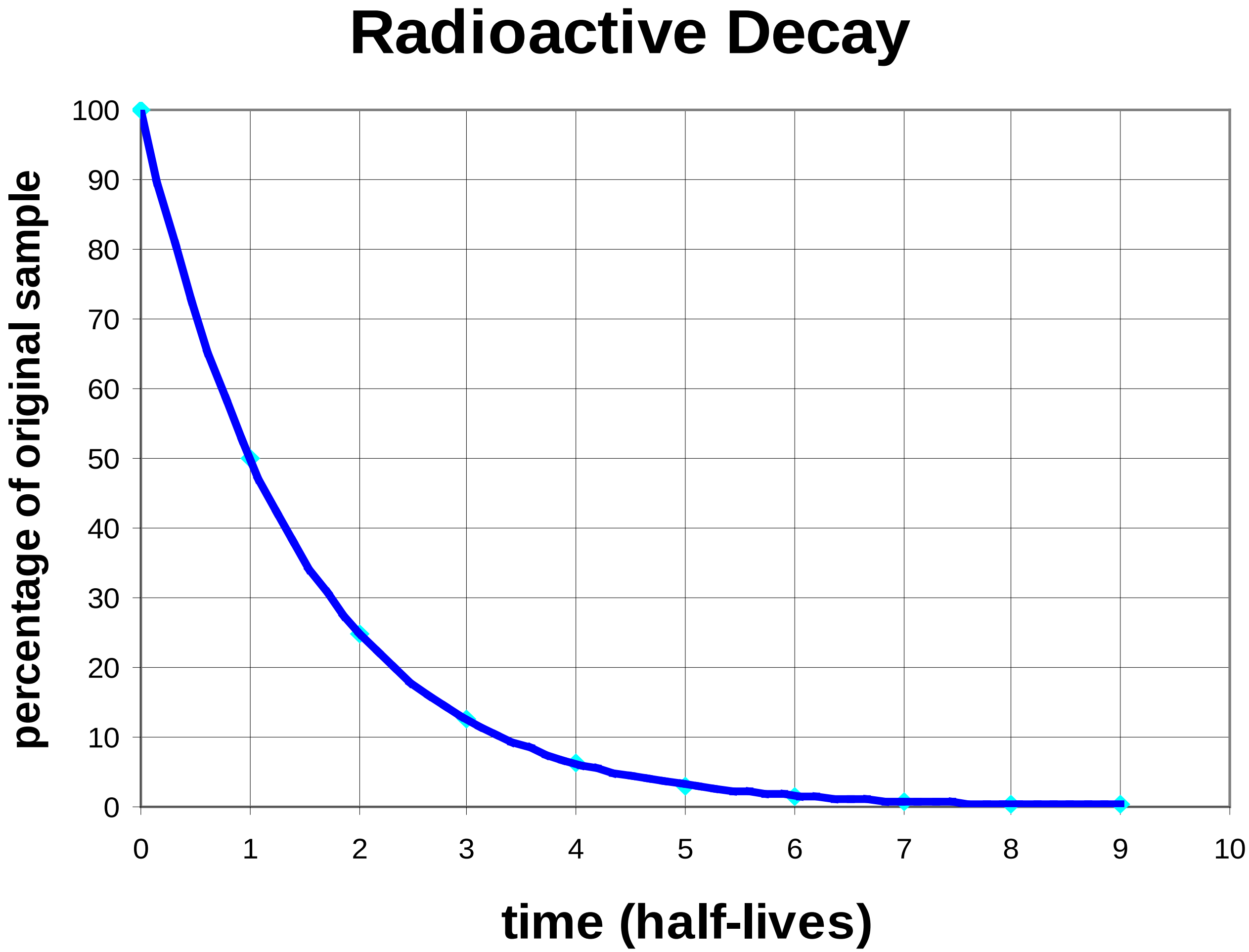
Nuclide	Half-Life	Type of Decay
Th-232	1.4×10^{10} yr	alpha
U-238	4.5×10^{9} yr	alpha
C-14	5730 yr	beta
Rn-220	55.6 sec	alpha
Th-219	1.05×10^{-6} sec	alpha

Pattern for Radioactive Decay

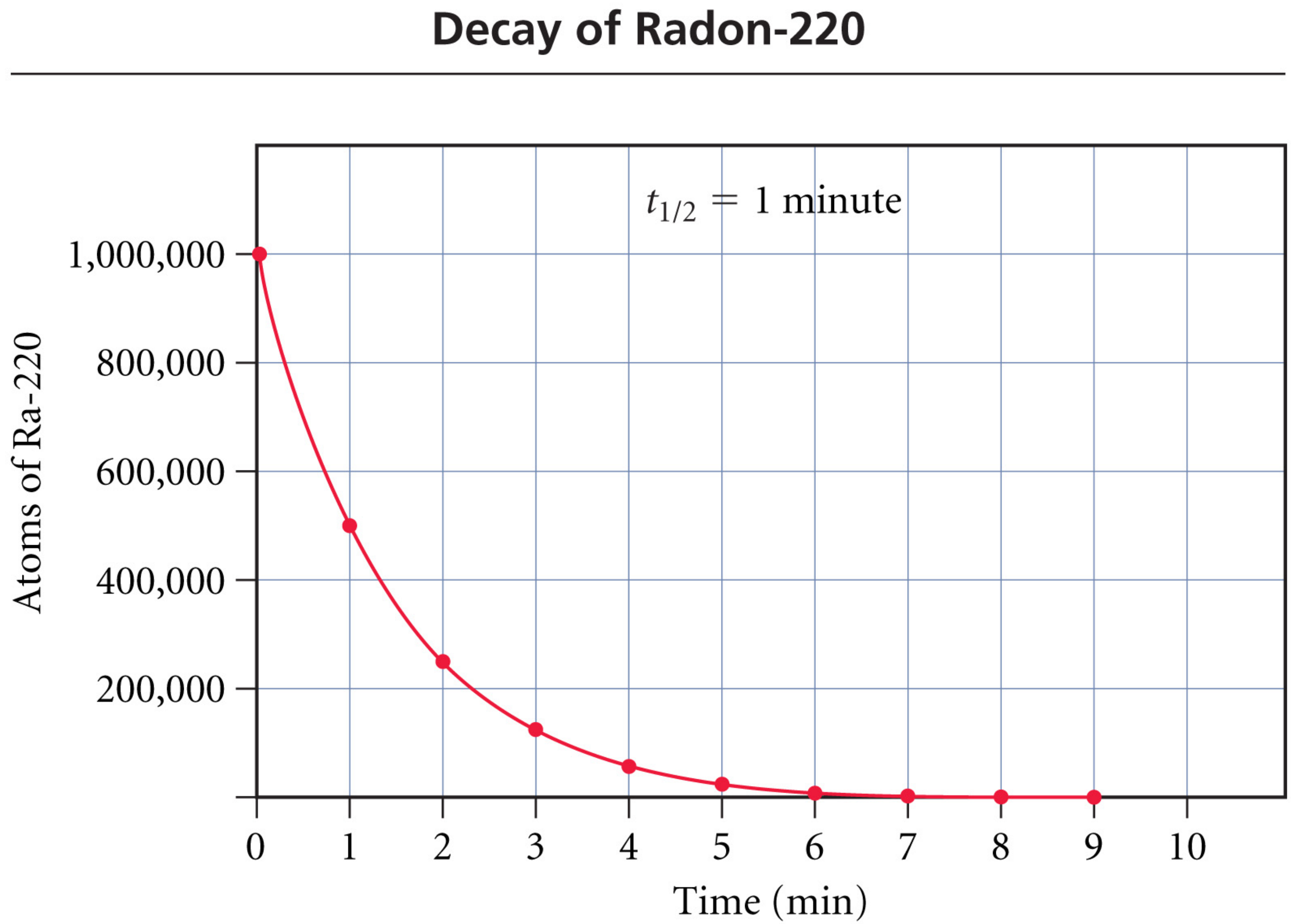


Half-Life

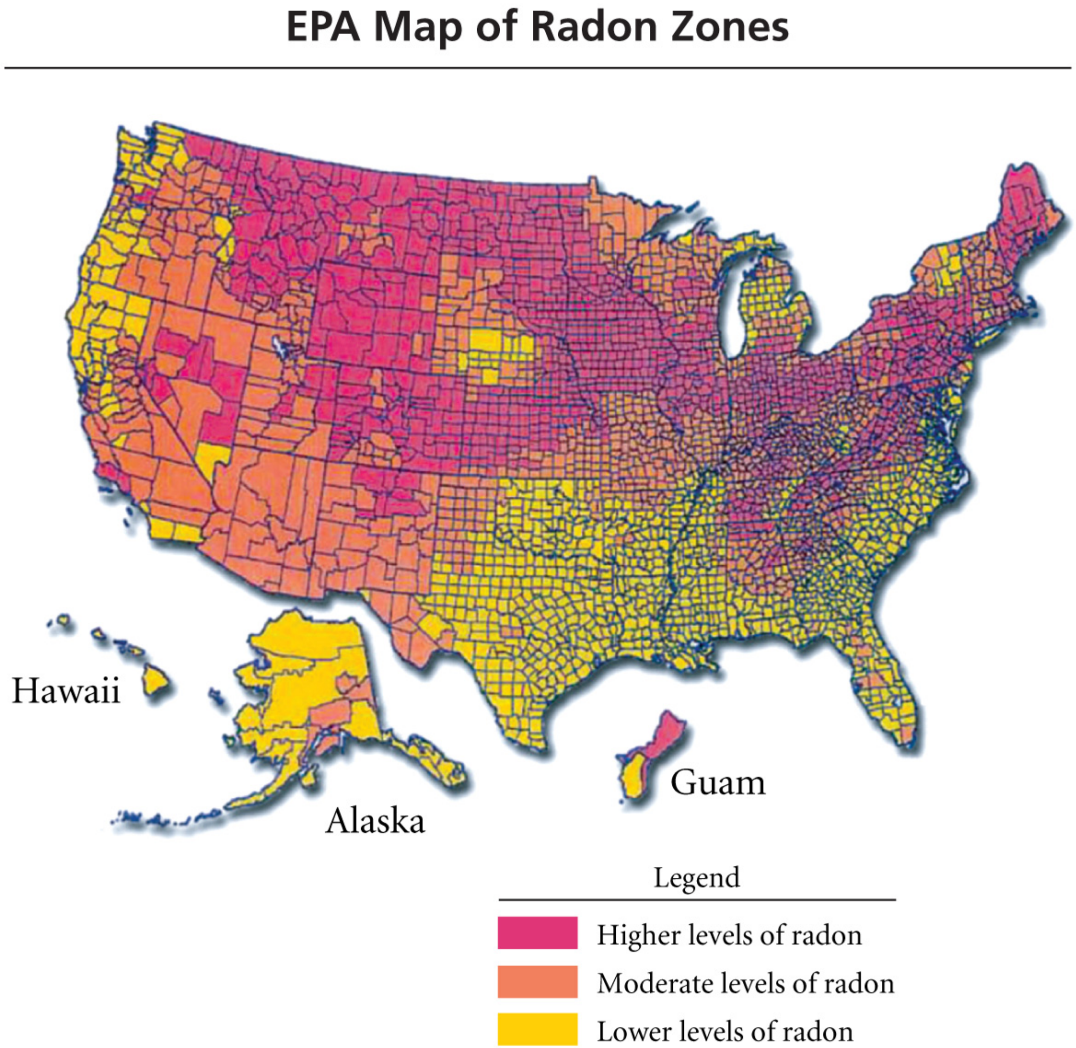
half of the radioactive atoms decay each half-life



Pattern for Radioactive Decay



Radon in the U.S.



Object Dating

- mineral (geological)
  - ✓ compare the amount of U-238 to Pb-206
  - ✓ compare amount of K-40 to Ar-40
- archaeological (once living materials)
  - ✓ compare the amount of C-14 to C-12
  - ✓ C-14 radioactive with half-life = 5730 yrs.
  - ✓ while substance living, C-14/C-12 fairly constant
    - ➢ CO_2 in air ultimate source of all C in organism
    - ➢ atmospheric chemistry keeps producing C-14 at the nearly the same rate it decays
  - ✓ once dies C-14/C-12 ratio decreases
  - ✓ limit up to 50,000 years

Radiocarbon Dating
C-14 Half-Life = 5730 yrs

% C-14 (relative to living organism)	Number of Half-Lives	Time (yrs)
100.0	0	0
50.0	1	5,730
25.00	2	11,460
12.50	3	17,190
6.250	4	22,920
3.125	5	28,650
1.563	6	34,380

Radiocarbon Dating

% C-14 (compared to living organism)	**Object's Age (in years)**
100%	0
90%	870
80%	1850
60%	4220
50%	5730
40%	7580
25%	11,500
10%	19,000
5%	24,800
1%	38,100

Nonradioactive Nuclear Changes

- a few nuclei are so unstable that if their nucleus is hit just right by a neutron, the large nucleus splits into two smaller nuclei - this is called **fission**
- small nuclei can be accelerated to such a degree that they overcome their charge repulsion and smash together to make a larger nucleus - this is called **fusion**
- **both fission and fusion release enormous amounts of energy**
  - ✓ fusion releases more energy per gram than fission

Lise Meitner

Biological Effects of Radiation

- Radiation is 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 a genetic defect in offspring

Measuring Radiation Exposure

- the **curie (Ci)** is an exposure of 3.7 x 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 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	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**

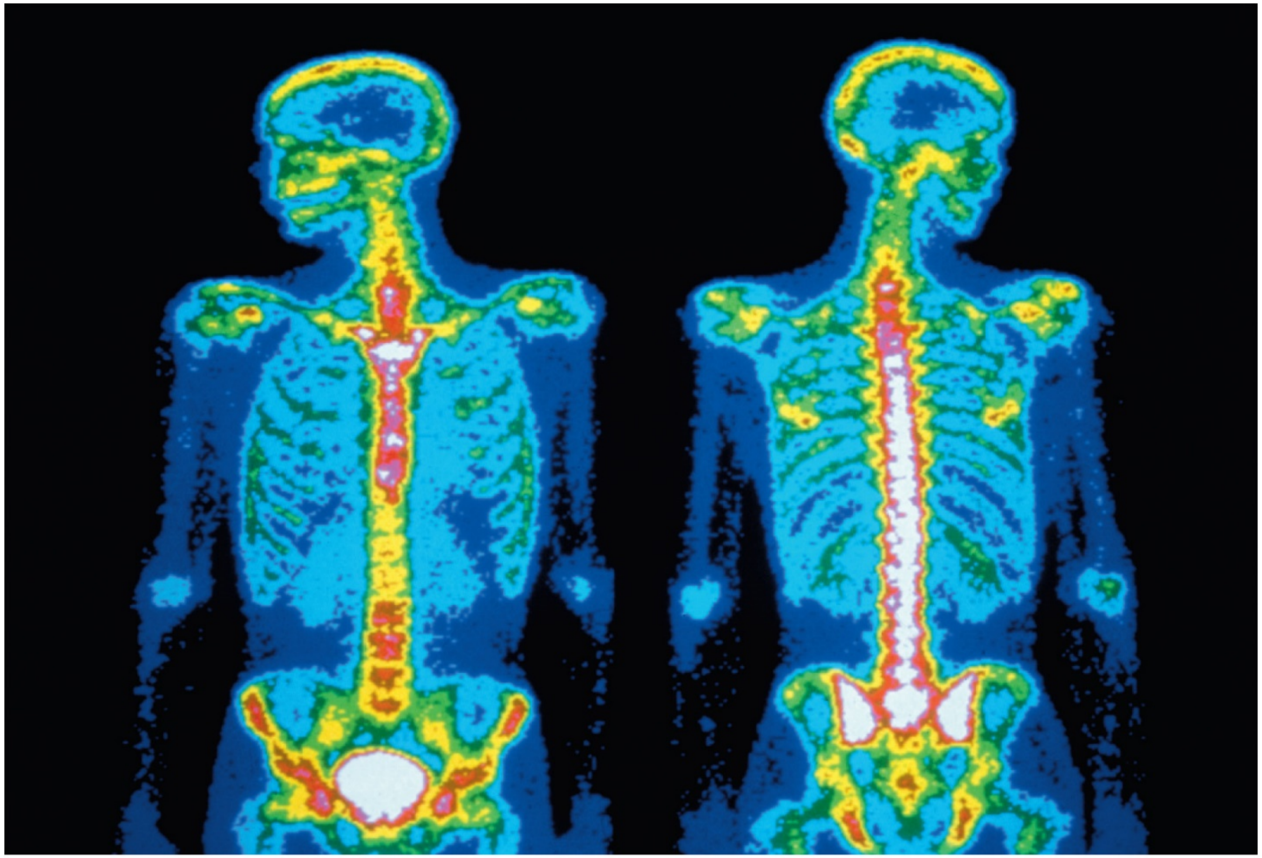
Dose (rems)	Probable Outcome
20-100	decreased white blood cell count; possible increased cancer risk
100-400	radiation sickness; increased cancer risk
500+	death

Medical Uses of Radioisotopes, Diagnosis

- radiotracers
  - ✓ certain organs absorb most or all of a particular element
  - ✓ can measure the amount absorbed by using tagged isotopes of the element and a Geiger counter
  - ✓ use radioisotope with short half-life
  - ✓ use radioisotope low ionizing
    - ➢ beta or gamma

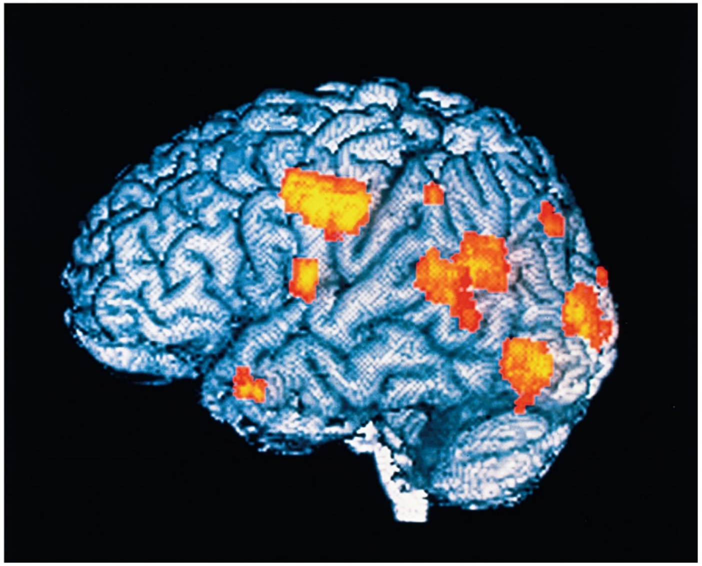
Nuclide	Half-life	Organ/System
Iodine-131	8.1 days	thyroid
Iron-59	45.1 days	red blood cells
Molybdenum-99	67 hours	metabolism
Phosphorus-32	14.3 days	eyes, liver
Strontium-87	2.8 hours	bones
Technetium-99	6 hours	heart, bones, liver, lungs

Bone Scans



Medical Uses of Radioisotopes, Diagnosis

- PET scan
  - ✓positron emission tomography
  - ✓F-18 in glucose
  - ✓brain scan and function



Medical Uses of Radioisotopes, Treatment - Radiotherapy

- cancer treatment
  - ✓ cancer cells more sensitive to radiation than healthy cells
  - ✓ **brachytherapy**
    - ➢ place radioisotope directly at site of cancer
  - ✓ **teletherapy**
    - ➢ use gamma radiation from Co-60 outside to penetrate inside
    - ➢ IMRT
  - ✓ **radiopharmaceutical therapy**
    - ➢ use radioisotopes that concentrate in one area of the body

Gamma Ray Treatment

Intensity-Modulated Radiation Therapy

- use precisely controlled x-ray from a linear accelerator to irradiate a malignant tumor
- designed to conform to the 3-D shape of the tumor

Nonmedical Uses of Radioactive Isotopes

- smoke detectors
  - ✓ Am-241
  - ✓ smoke blocks ionized air, breaks circuit
- insect control
  - ✓ sterilize males
- food preservation
- radioactive tracers
  - ✓ follow progress of a “tagged” atom in a reaction
- chemical analysis
  - ✓ neutron activation analysis

Nonmedical Uses of Radioactive Isotopes

- authenticating art object
  - ✓ many older pigments and ceramics were made from minerals with small amounts of radioisotopes
- crime scene investigation
- measure thickness or condition of industrial materials
  - ✓ corrosion
  - ✓ track flow through process
  - ✓ gauges in high temp processes
  - ✓ weld defects in pipelines
  - ✓ road thickness

Nonmedical Uses of Radioactive Isotopes

- agribusiness
  - ✓ develop disease-resistant crops
  - ✓ trace fertilizer use
- treat computer disks to enhance data integrity
- nonstick pan coatings
- photocopiers to help keep paper from jamming
- sterilize cosmetics, hair products, and contact lens solutions and other personal hygiene products