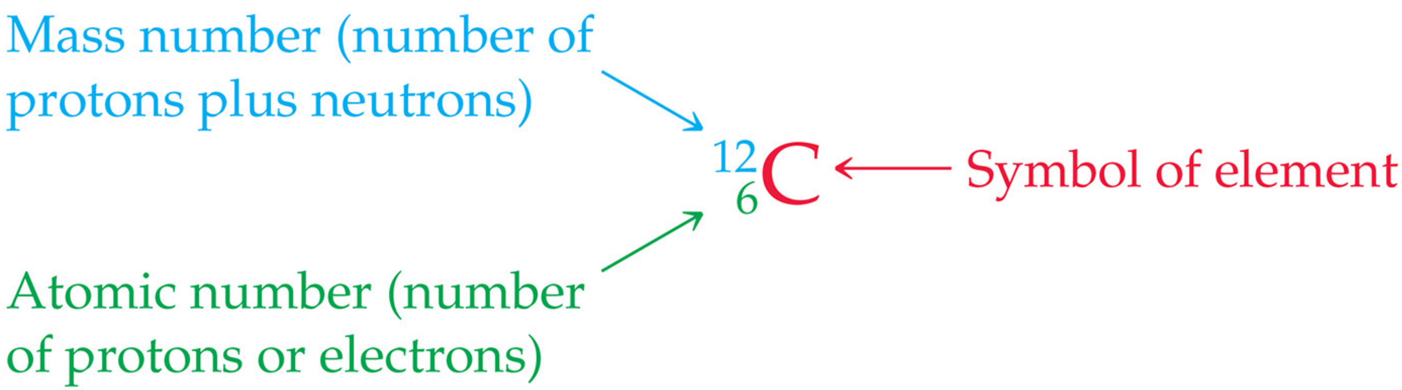
Chapter 21

Nuclear Chemistry

21.1 Radioactivity and Nuclear Equations
Review: how we write isotopes



- The number of protons and neutrons together is the **mass number**.
- The number of protons is the **atomic number**.
- The nucleus has two types of **nucleons:**
  - Protons (+1 charge)
  - neutrons. (no charge)

Isotopes

- Atoms of the same element don't always have the same mass
- Why? Different numbers of **neutrons** in those atoms.
  - Example: three naturally occurring isotopes of uranium:
    - Uranium-234, Uranium-235, Uranium-238
- Some nuclei spontaneously change,
  - emit radiation.
  - They are said to be **radioactive**.
  - **radionuclides**.

Nuclear Equations

- Nuclear reactions:
  - Reactions of the ***nucleus***
- Chemical reactions:
  - atoms (“stuff”) and charges must balance.
- Nuclear reactions:
  - atomic number and mass number must balance.
    - atomic number balances ***charge***
    - Mass number balances atoms (“stuff”)

Properties of Radioactive Decay

Three types:

Alpha (α)
Beta (β)
Gamma (γ)

Table 21.1 Properties of Alpha, Beta, and Gamma Radiation

Property	α	β	γ
Charge	2+	1−	0
Mass	6.64×10^{-24} g	9.11×10^{-28} g	0
Relative penetrating power	1	100	10,000
Nature of radiation	$^{4}_{2}$He nuclei	Electrons	High-energy photons

Alpha Radiation

Alpha decay is the loss of an α-particle (He-4 nucleus, two protons and two neutrons): ${}^{4}_{2}\mathrm{He}$

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

- Balancing:
  - mass number: $238 = 234 + 4$
  - atomic number: 92 = 90 + 2

The **atomic number** identifies the product, i.e., 90 is Th (thorium)

Beta Radiation

Beta decay is the loss of a β-particle (a high-speed **electron** emitted by the nucleus): ${}^{0}_{-1}\beta$ or ${}^{0}_{-1}\mathrm{e}$

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

- Balancing:
  - atomic number: $53 = 54 + (-1)$
  - mass number: $131 = 131 + 0$

Gamma Radiation

Gamma emission:

loss of a high-energy **photon**

almost always accompanies loss of a nuclear particle (α or β or positron decay):

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

No loss in mass.

No gain/loss in charge

Often not shown in nuclear equations.

Positron Emission

positron,

has the same mass as an electron.

but opposite charge (+1) $^{0}_{1}e$

$$^{11}_{6}C \rightarrow ^{11}_{5}B + ^{0}_{+1}e$$

- Balancing:
  - atomic number: $6 = 5 + 1$
  - mass number: $11 = 11 + 0$

Not a proton!

Basically a proton losing its charge becoming a neutron.

Electron Capture

An electron from the surrounding electron cloud is absorbed into the nucleus during **electron capture**.

$$ {}^{81}_{37}\mathrm{Rb} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{81}_{36}\mathrm{Kr} $$

- Balancing:
  - atomic number: $37 + (-1) = 36$
  - mass number: $81 + 0 = 81$

Types of Radioactive Decay

Table 21.3 Types of Radioactive Decay

Type	Nuclear Equation	Change in Atomic Number	Change in Mass Number
Alpha emission	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	-2	-4
Beta emission	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$	$+1$	Unchanged
Positron emission	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$	-1	Unchanged
Electron capture*	${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}Y$	-1	Unchanged

*The electron captured comes from the electron cloud surrounding the nucleus.

What's happening in Nuclear Reactions

- Production of beta particles converts **proton** into neutron:

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

- **positron** emission Converts a proton to a neutron:

$$^{1}_{1}\mathrm{p} \rightarrow ^{1}_{0}\mathrm{n} + ^{0}_{+1}\mathrm{e} \quad \text{or} \quad \mathrm{p} \rightarrow \mathrm{n} + \beta^{+}$$

- Electron capture converts a **proton** into a neutron:

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

Summary of Kinds of Nuclear Particles

Table 21.2 Particles Found in Nuclear Reactions

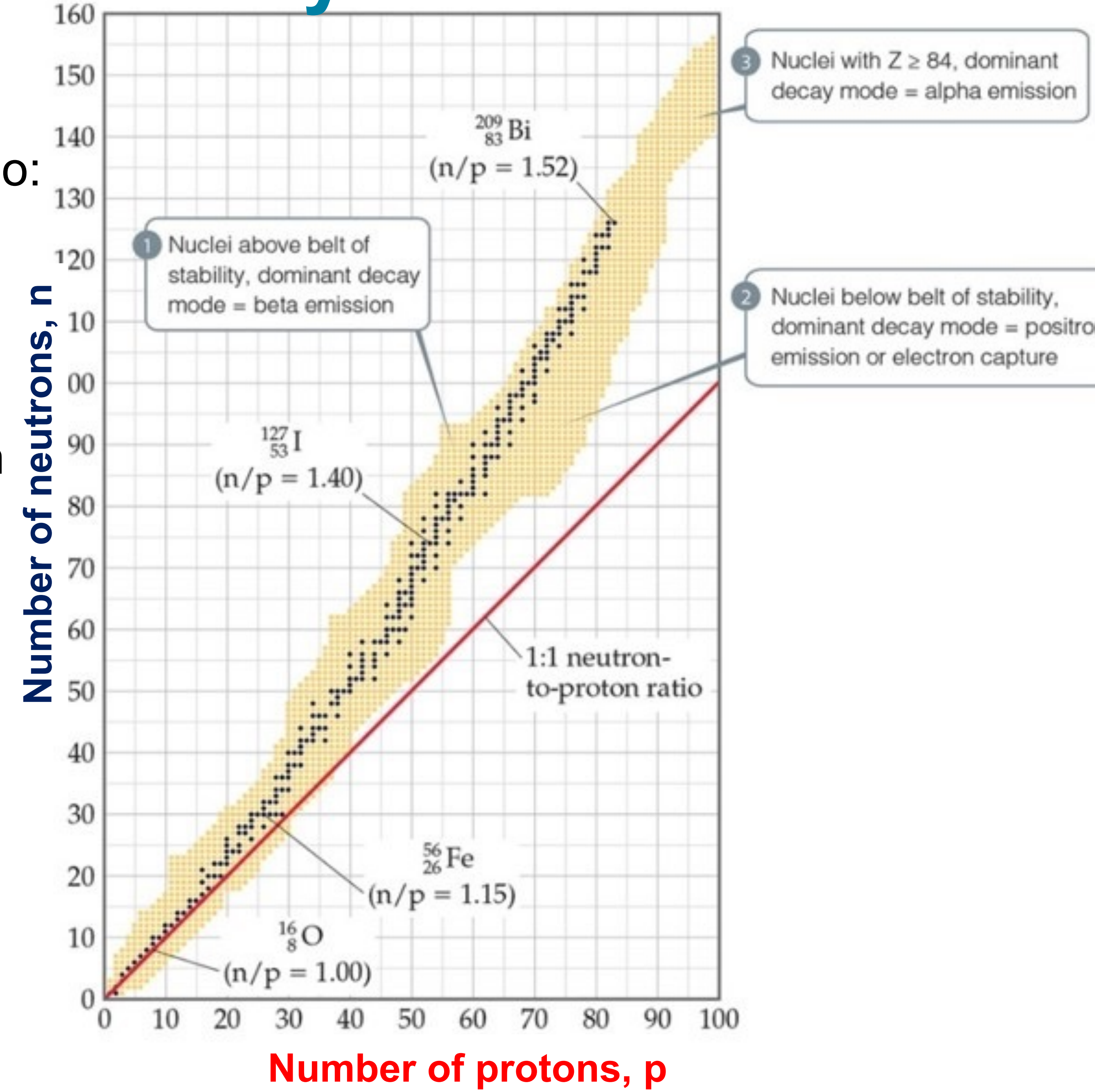
Particle	**Symbol**
Neutron	${}^{1}_{0}n$ or n
Proton	${}^{1}_{1}H$ or p
Electron	${}^{0}_{-1}e$
Alpha particle	${}^{4}_{2}He$ or α
Beta particle	${}^{0}_{-1}e$ or β^{-}
Positron	${}^{0}_{+1}e$ or β^{+}

21.2 Patterns of Nuclear Stability

- Protons in the nucleus repel each other because of charge.
- **The strong nuclear force** keeps the nucleus together. It's the nuclear glue. Comes from both protons and neutrons.
- **Neutrons** provide **strong nuclear force** *without repulsion*.
- But too many **Neutrons**, also leads to ***instability.***

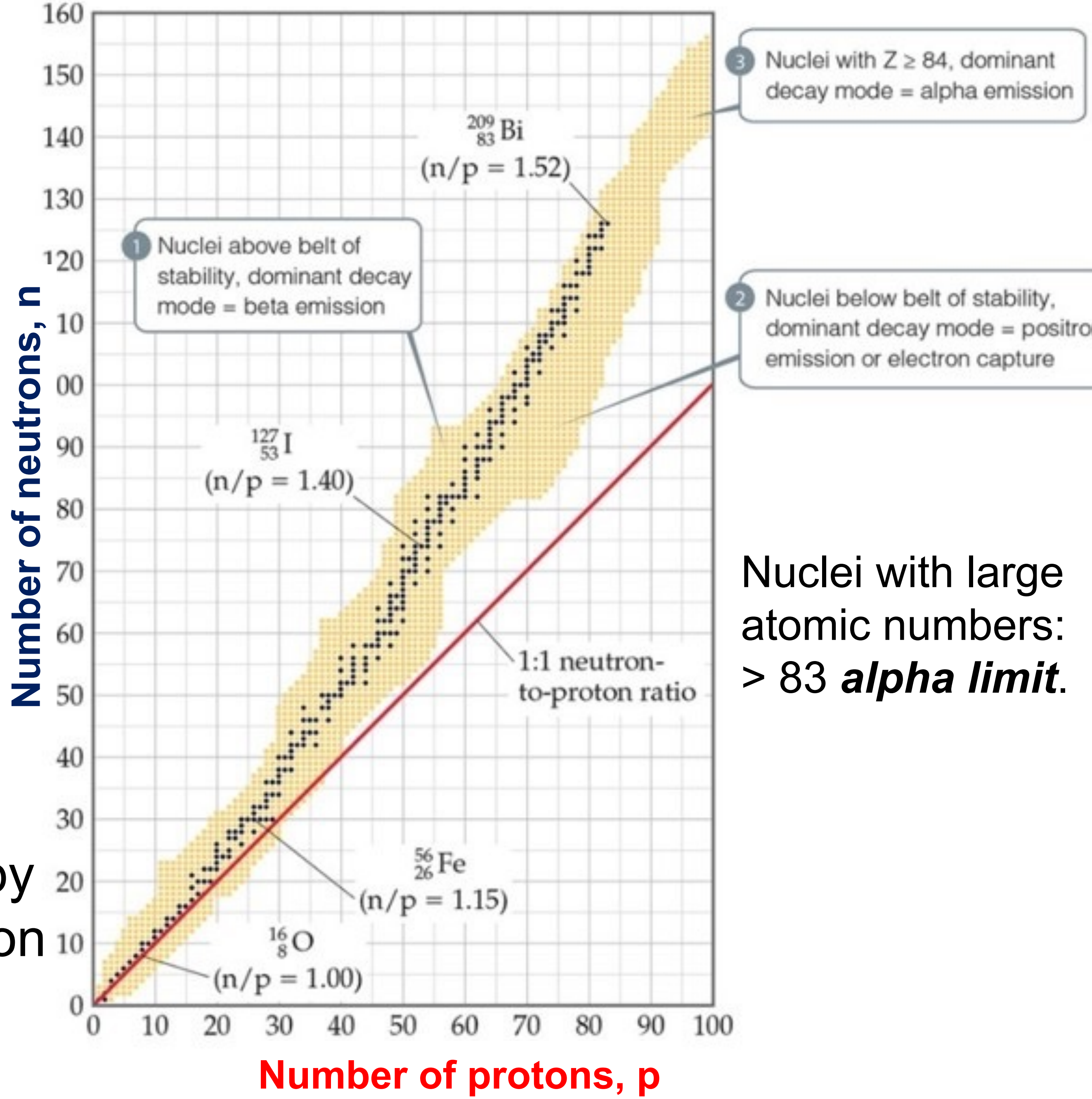
Valley of Stability

- Smaller nuclei
- Proton/neutron ratio: **1:1**
- Larger nuclei:
  - More **protons**
  - More repulsion
  - Need **more Neutrons.**
- **belt of stability.**
- **Zone of stability**
  - It shows which nuclides would be stable.



Unstable Nuclei

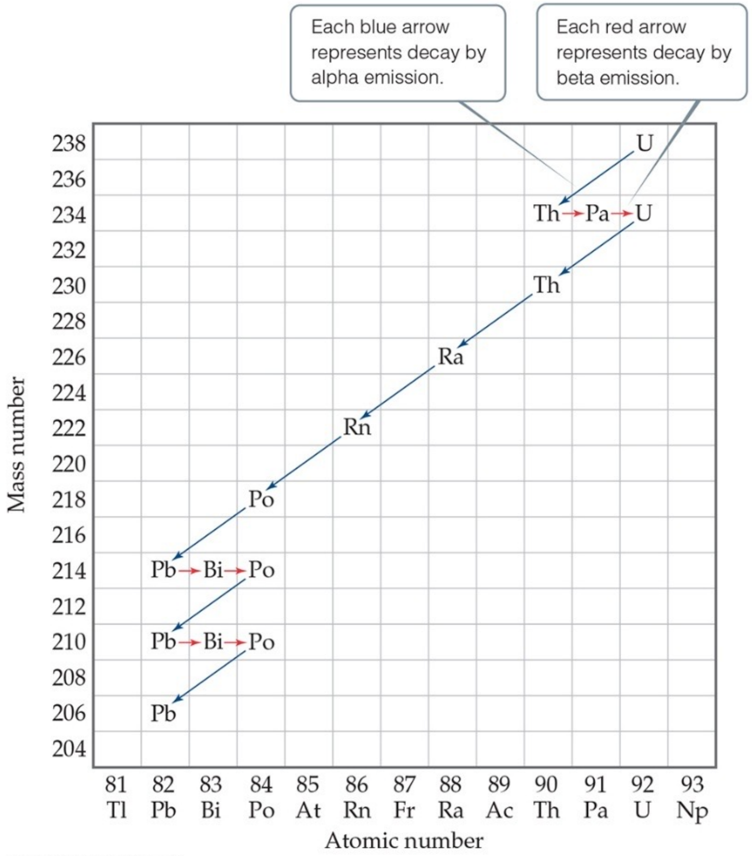
- Nuclei above the belt:
  - have too many neutrons.
  - decay by beta emission.
  - Neutron -> proton + β^{-}
- Nuclei below the belt:
  - have too many protons.
  - Usually decay by positron emission or electron capture.



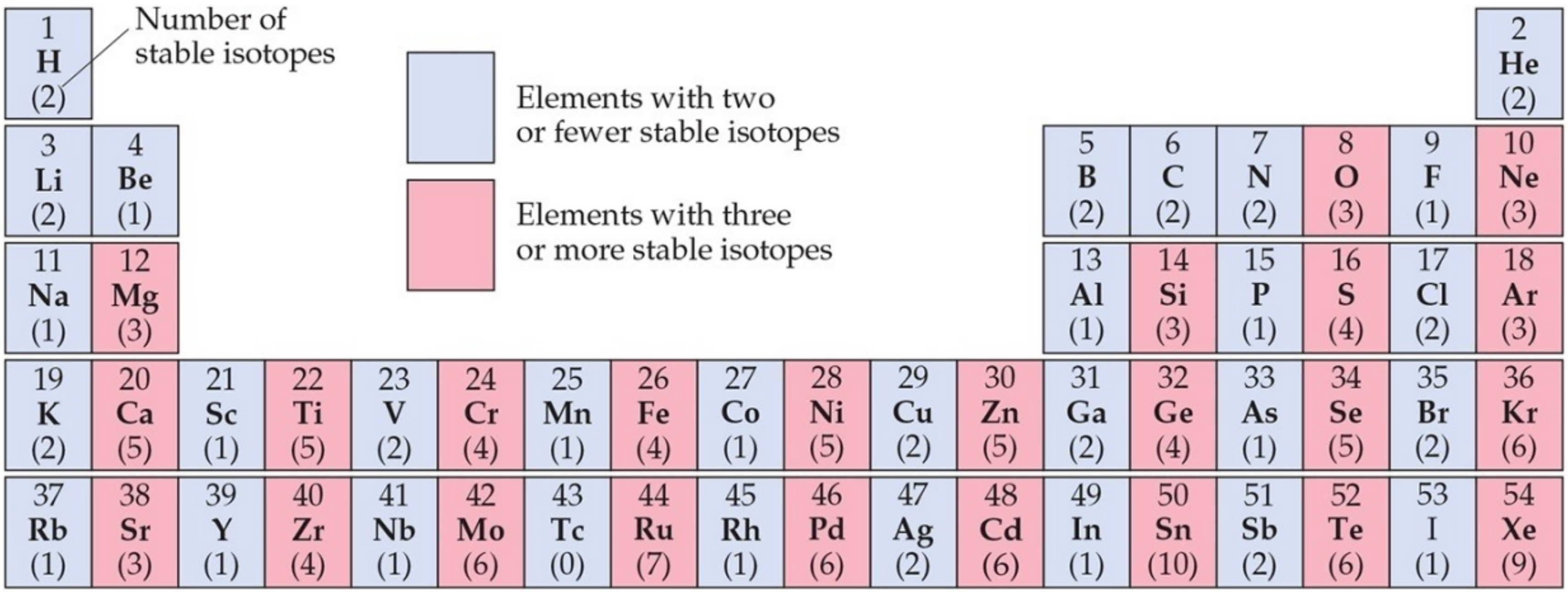
Nuclei with large atomic numbers: > 83 ***alpha limit***.

Radioactive Decay Chains

- Some radioactive nuclei cannot stabilize by undergoing only one nuclear transformation.
- They undergo a series of decays until they form a stable nuclide (often a nuclide of lead).

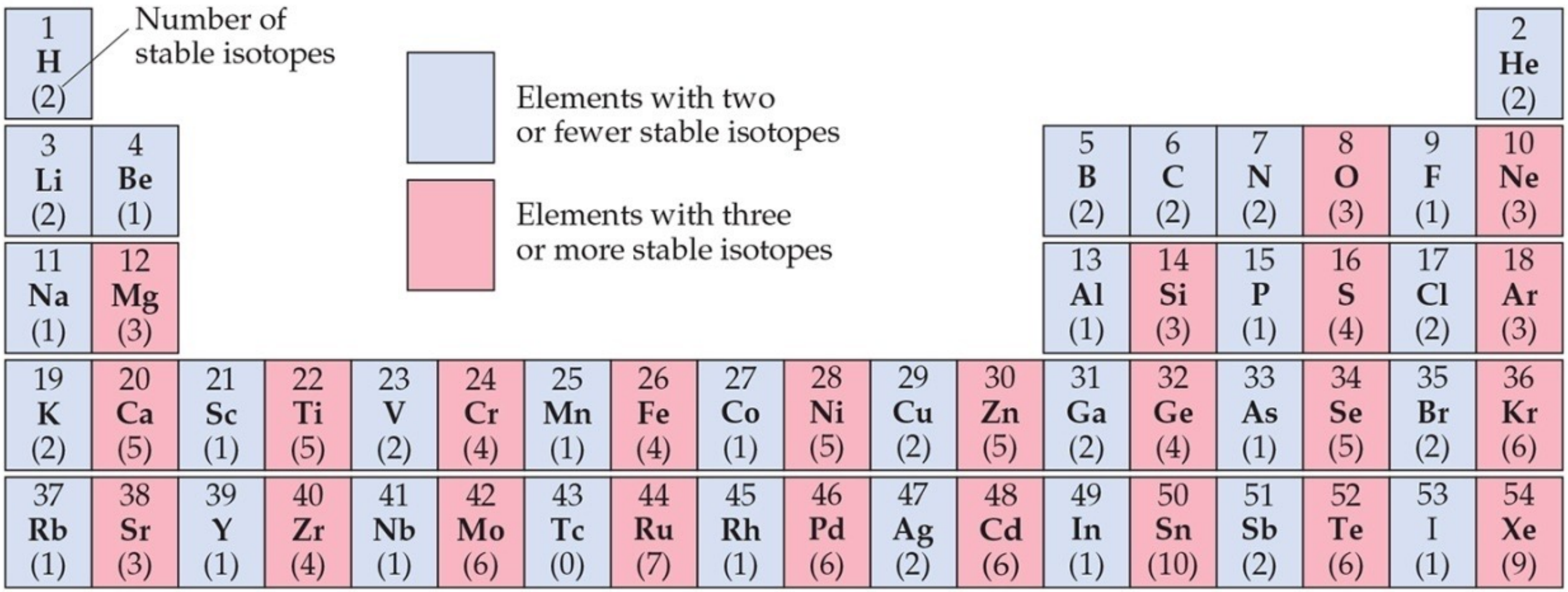


Stable Nuclei (1 of 2)



- **Magic numbers:**
  - 2, 8, 20, 28, 50, or 82 protons
  - 2, 8, 20, 28, 50, 82, or 126 **neutrons**
  - result in more stable nuclides.
- even numbers of protons and neutrons tend to be more stable than those with odd numbers.
- Why?

Stable Nuclei (1 of 2)



- **Magic numbers:**
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  - result in more stable nuclides.
- even numbers of protons and neutrons tend to be more stable than those with odd numbers.
- Why?
- ***Quantum mechanics (nothing is magic)***

Stable Nuclei (2 of 2)

Table 21.4 Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons

Number of Stable Isotopes	**Proton Number**	**Neutron Number**
157	Even	Even
53	Even	Odd
50	Odd	Even
5	Odd	Odd

21.3 Nuclear Transmutations

- Happens when nuclei ***collide with something.***
  - ***Another nucleus***
  - ***A neutron***
- Nuclear equations that represent nuclear transmutations are written in one of two ways:

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} \text{ or } {}^{14}_{7}\mathrm{N} + \alpha \rightarrow {}^{17}_{8}\mathrm{O} + \mathrm{p}$$

or

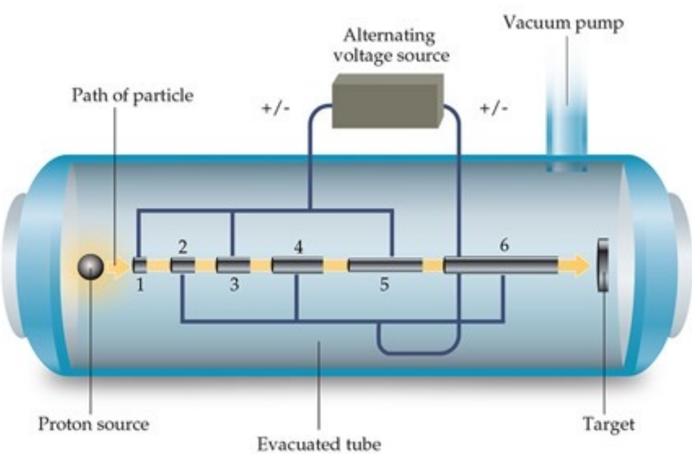
$$\overset{\text{Target nucleus}}{{}^{14}_{7}\mathrm{N}}(\underset{\text{Bombarding particle}}{\alpha}, \underset{\text{Ejected particle}}{\mathrm{p}})\overset{\text{Product nucleus}}{{}^{17}_{8}\mathrm{O}}$$

Accelerating Charged Particles

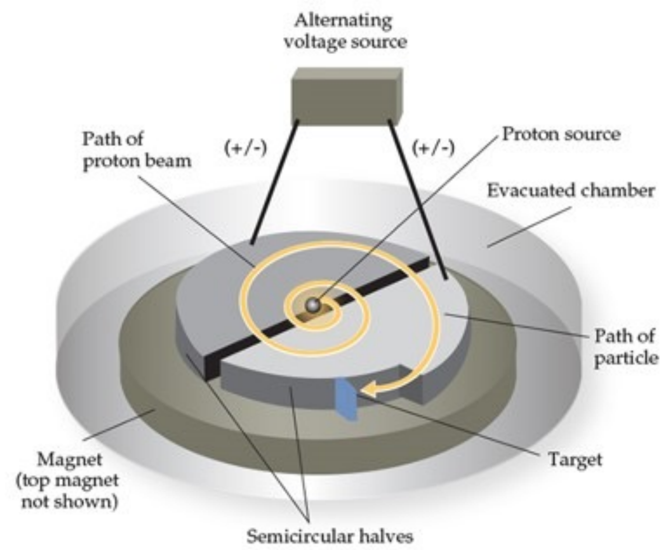
- **Particle accelerators** (“atom smashers”)
  – use strong magnetic and electric fields
  – make the particles move very fast (near speed of light).
- **linear accelerator**
  – **Accelerates in a straight line.**
- **Cyclotron** (like right next door!)
  – D-shaped magnets keep particles moving in a spiral.
- **synchrotron**
  – accelerates particles in a circle.

Particle Accelerators

Linear Accelerator



(a)



(a)

(b)

Stanford Linear Accelerator

(b)

Fermi lab (Chicago Ill.

Facility for Rare Isotopes (FRIB). MSU

The best facility for discovering new nuclei in the world

Other Nuclear Transmutations

- **Use of neutrons**:
  - Most synthetic isotopes are used in medicine
  - Made by bombarding neutrons at an element.
    - Because they’re neutral
      - You get more “bang” for your “bang”
- **Transuranium elements**:
  - Elements immediately after uranium
    - discovered by bombarding isotopes with neutrons.
  - Larger elements (atomic number higher than 110)
    - made by colliding large nuclei with light nuclei
      - *At high energy*.

Example problem: transmutation

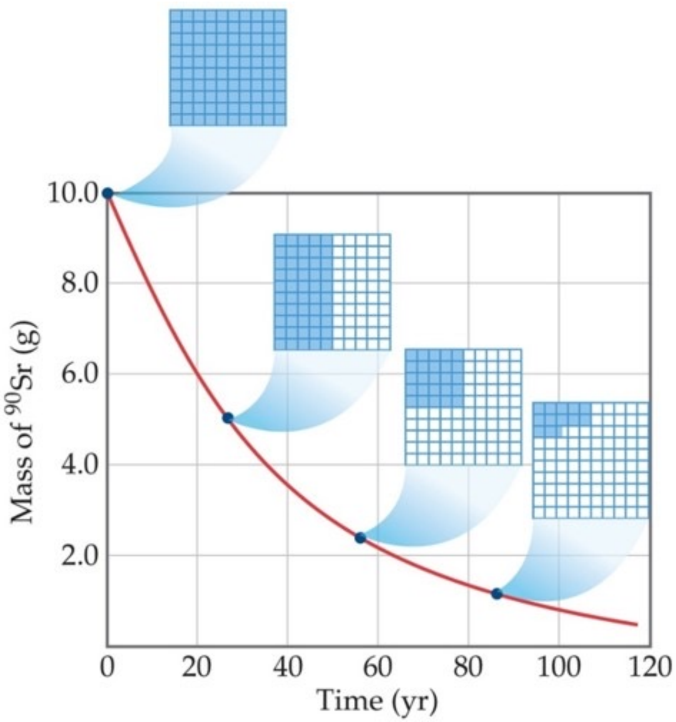
- **Write the nuclear reaction from this short form**

$$^{27}_{13}\text{Al}(\text{n}, \alpha)^{24}_{11}\text{Na}.$$

- $^{27}_{13}Al + n \rightarrow \, ^{24}_{11}Al + \, ^{4}_{2}He$

21.4 Kinetics of Radioactive Decay

- All Radioactive decay is a first-order process.
- The kinetics obey the equation: $\ln \frac{N_t}{N_0} = -kt$
- Half-life is the time required for half of a radionuclide sample to decay.
- $ln\frac{N_t}{N_0} = ln\frac{0.5}{1} = -kt_{\frac{1}{2}} = -.693$
- $\frac{0693}{t_{1/2}} = k$

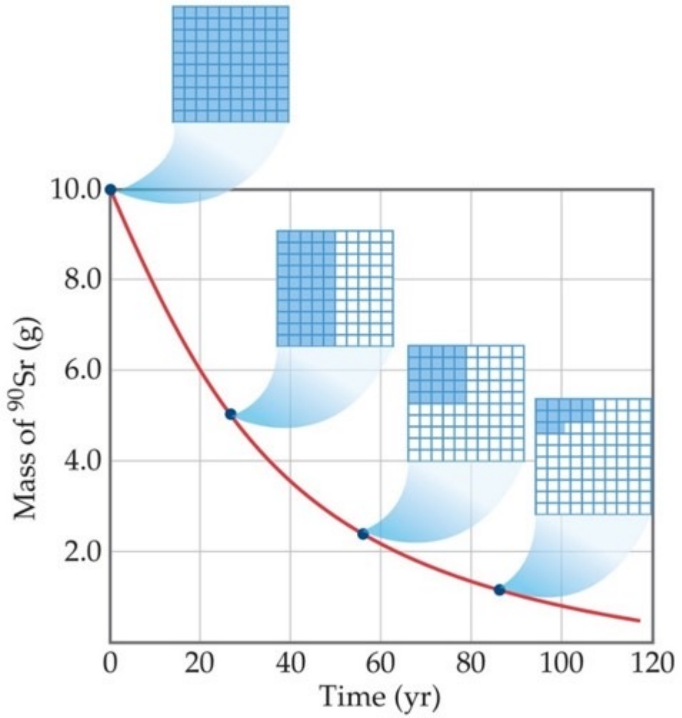


21.4 Kinetics of Radioactive Decay Example:

The half-life of cobalt-60 is 5.27 yr.

How much of a 1.000-mg sample of cobalt-60 is left after 15.81 yr?

- $ln\frac{N_t}{N_0} = -kt$
- $e^{-kt} = \frac{N_t}{N_0}$
- $ln\frac{0.5}{1} = -kt_{\frac{1}{2}} = -.693$
- $\frac{0.693}{t_{1/2}} = k$
- $\frac{0.693}{5.27yr} = k = 0.1315yr^{-1}$
- $N_0\ e^{-kt} = N_t = (1mg)e^{-(0.1315yr^{-1})15.81yr} = 0.125\,mg$



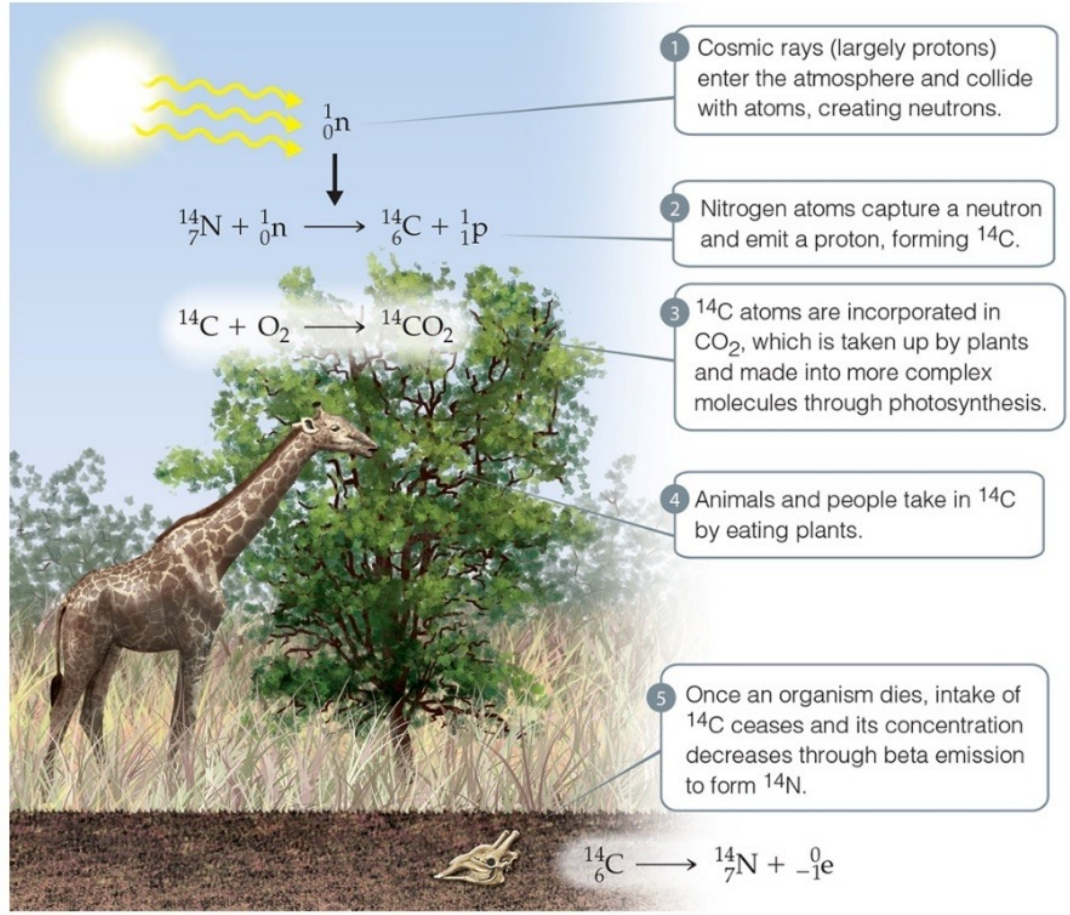
Some Radioactive Isotopes

Table 21.5 The Half-Lives and Type of Decay for Several Radioisotopes

	Isotope	Half-Life (yr)	Type of Decay
Natural radioisotopes	$^{238}_{92}U$	4.5×10^9	Alpha
Natural radioisotopes	$^{235}_{92}U$	7.0×10^8	Alpha
Natural radioisotopes	$^{232}_{90}Th$	1.4×10^{10}	Alpha
Natural radioisotopes	$^{40}_{19}K$	1.3×10^9	Beta
Natural radioisotopes	$^{14}_{6}C$	5700	Beta
Synthetic radioisotopes	$^{239}_{94}Pu$	24,000	Alpha
Synthetic radioisotopes	$^{137}_{55}Cs$	30.2	Beta
Synthetic radioisotopes	$^{90}_{38}Sr$	28.8	Beta
Synthetic radioisotopes	$^{131}_{53}I$	0.022	Beta

Radiometric Dating

- First-order kinetics and half-life information let us date objects using a “nuclear clock.”
- **Carbon dating**: The half-life of C-14 is 5730 years. I is limited to objects up to about 50,000 years old. After this time there is too little radioactivity to measure.
- Other isotope decays can be used, i.e., U-238 to Pb-206.



- As long as your alive
  - $^{14}C/^{12}C$ ratio constant.
- Once you die:
  - ^{14}C decays.

21.4 Using Radioactive Decay for dating Example:

A rock contains 0.257 mg of lead-206 for every milligram of uranium-238. The half-life for the decay of uranium-238 to lead-206 is 4.5×10^9 yr. How old is the rock?

- *Need: How much ^{238}U originally?*
- *Assume: all ^{206}Pb was originally ^{238}U.*
  - *Find out moles ^{206}Pb: 0.257mg/206 mg/mMol = 0.00125 mMol ^{206}Pb=mMol ^{238}U.*
  - *0.00125mMOL(238mg/mMOL)=0.297 mg ^{238}U.*
  - *Total ^{238}U: 1 mg + 0.297 = 1.297 mg.*
- $ln\frac{N_t}{N_0} = -kt = -\frac{0.693}{t_{\frac{1}{2}}}t = -\frac{0.693}{4.5x10^9}t = ln\frac{1mg}{1.297mg} = -.260$
- $t = 1.7x10^9$ *years.*

Measuring Radioactivity: Units

- **Activity** is the rate at which a sample decays.
- The units used to measure activity are as follows:
  - **Becquerel (Bq)**: one nuclear disintegration per second
  - **Curie (Ci):** defined as 3.7×10^{10} disintegrations per second. This is the rate of decay of 1 g of radium.

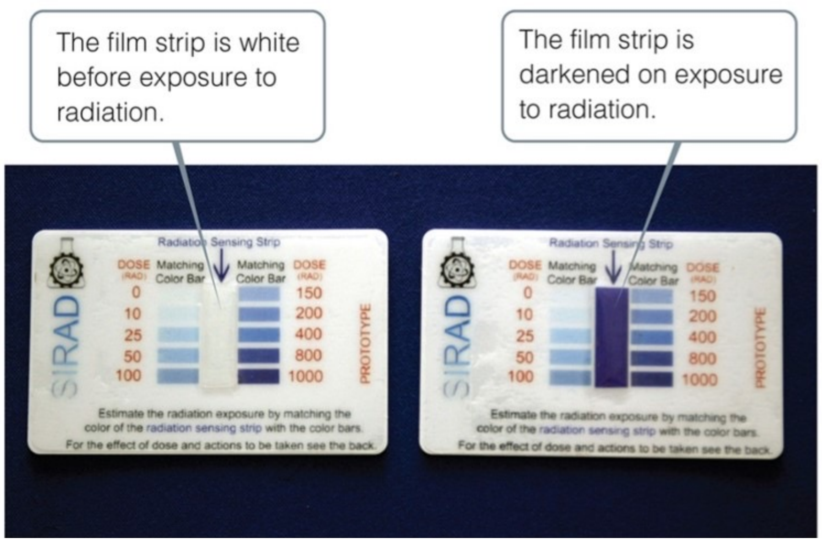
21.5 Detection of Radioactivity

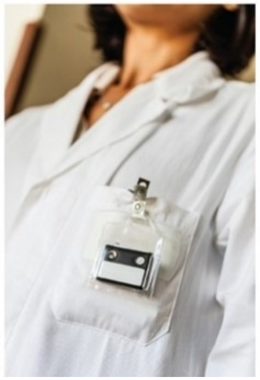
Methods:

- Film badges
- Geiger counters
- Phosphors (scintillation counters)
- Radiotracers (medicine)
- Positron emission tomography (PET scan)

Film Badges

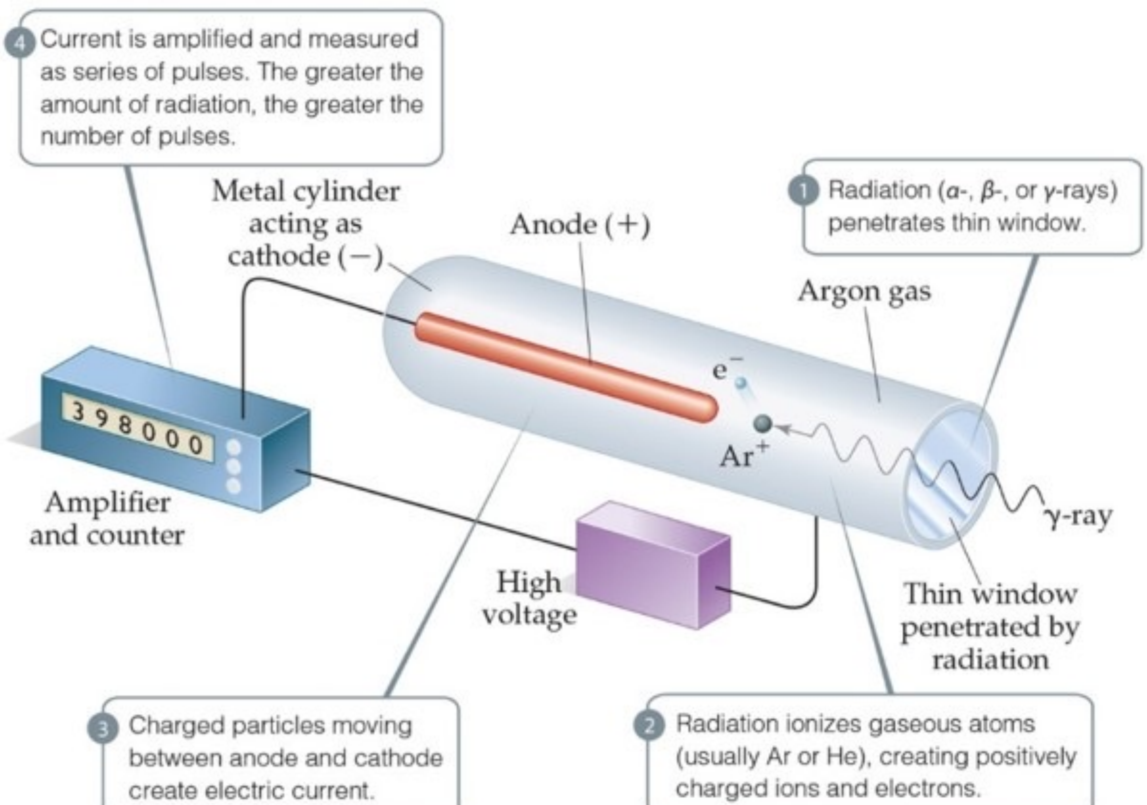
- Radioactivity was first discovered by Henri Becquerel because it fogged up a photographic plate.
- Exposure to radioactivity is detected on film.
  - Film badges are used by people who work with radioactivity to measure their own exposure over time.





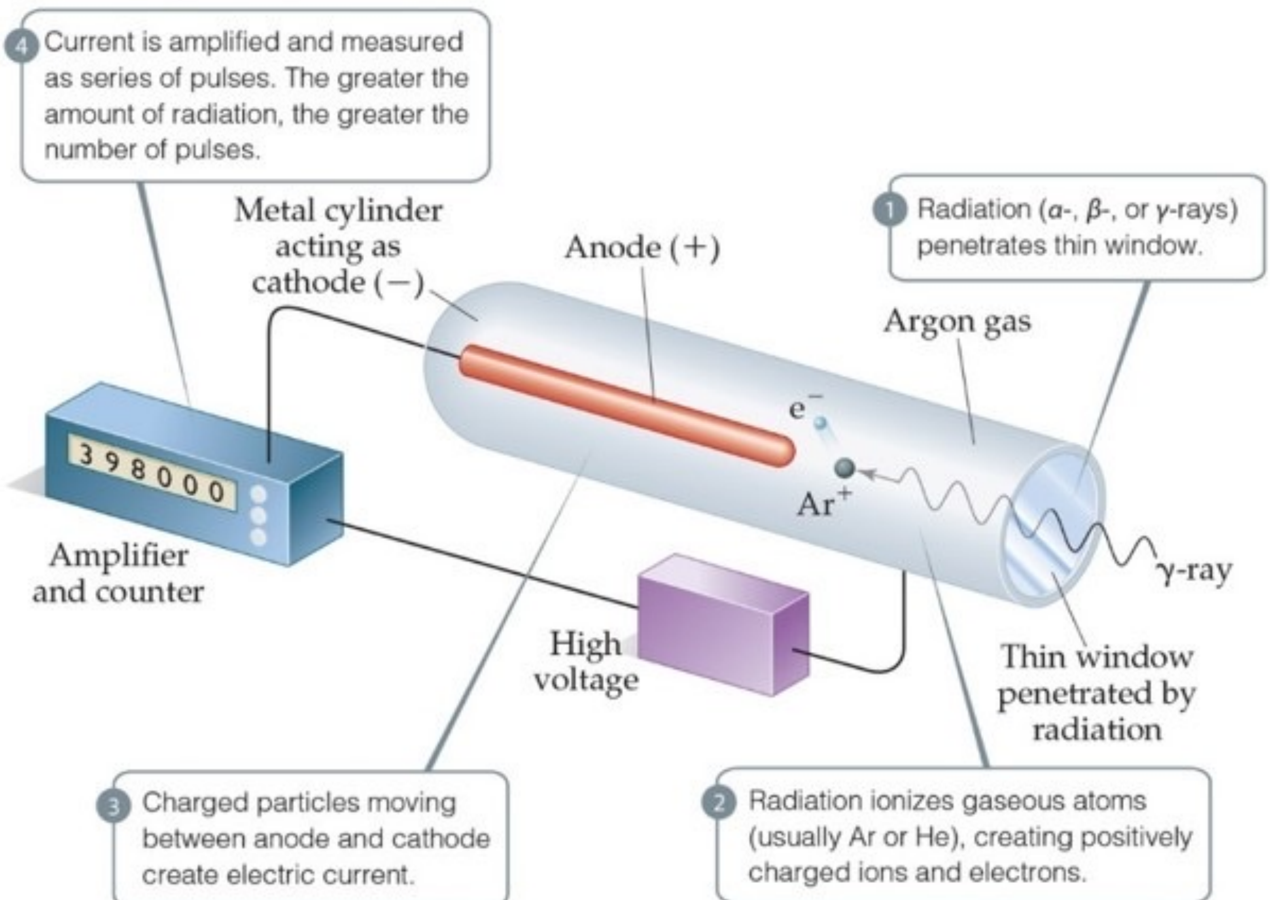
Geiger Counter

- A **Geiger counter** measures the amount of activity present in a radioactive sample.
- Radioactivity enters a window and creates ions in a gas.
- The ions result in an electric current that is measured and recorded by the instrument.



Geiger Counter

- Note:
  - 1 gamma ray photon gives 1 e^-
  - 1 nuclear event typically gives off 1 gamma ray.
    - Energy of gamma ray can vary, but usually only 1.



21.4 Using Radioactive Decay for dating Example 2 carbon dating:

A wooden object from an archeological site is subjected to radiocarbon dating. The activity due to ^{14}C is measured to be 11.6 disintegrations per second. The activity of a carbon sample of equal mass from fresh wood is 15.2 disintegrations per second. The half-life of ^{14}C is 5730 yr. What is the age of the archeological sample?

- *Assumption: disintegrations/sec directly proportional to amount of radioactive stuff.*
- $ln\frac{N_t}{N_0} = ln\frac{disint_t}{disint_0} = -kt = -\frac{0.693}{t_{\frac{1}{2}}}t = -\frac{0.693}{5730yr}t = ln\frac{11.6}{15.2} = -0.270$
- $t = 0.270\frac{5730yr}{0.693} = 2235\ years.$

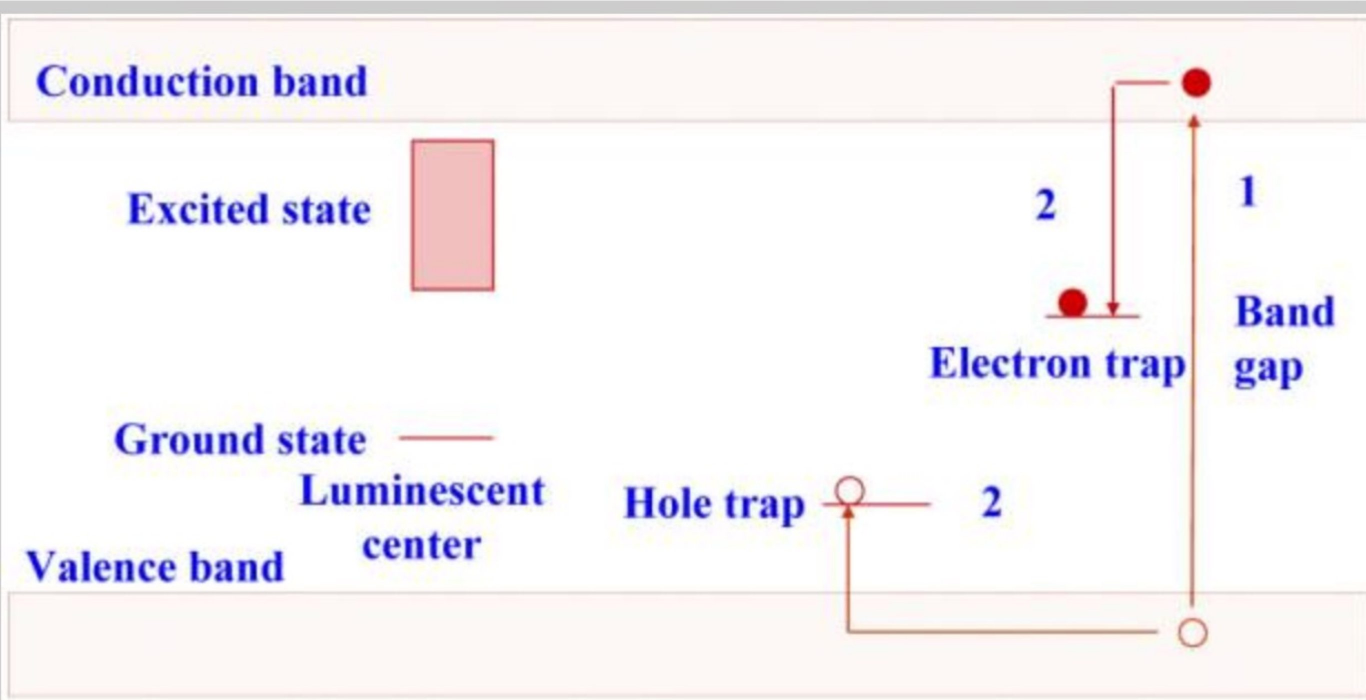
Recording radiation spatially: Phosphors

- Some substances absorb radioactivity and emit light. They are called **phosphors**.
- **scintillation counter.** converts the light to an electronic response for measurement.

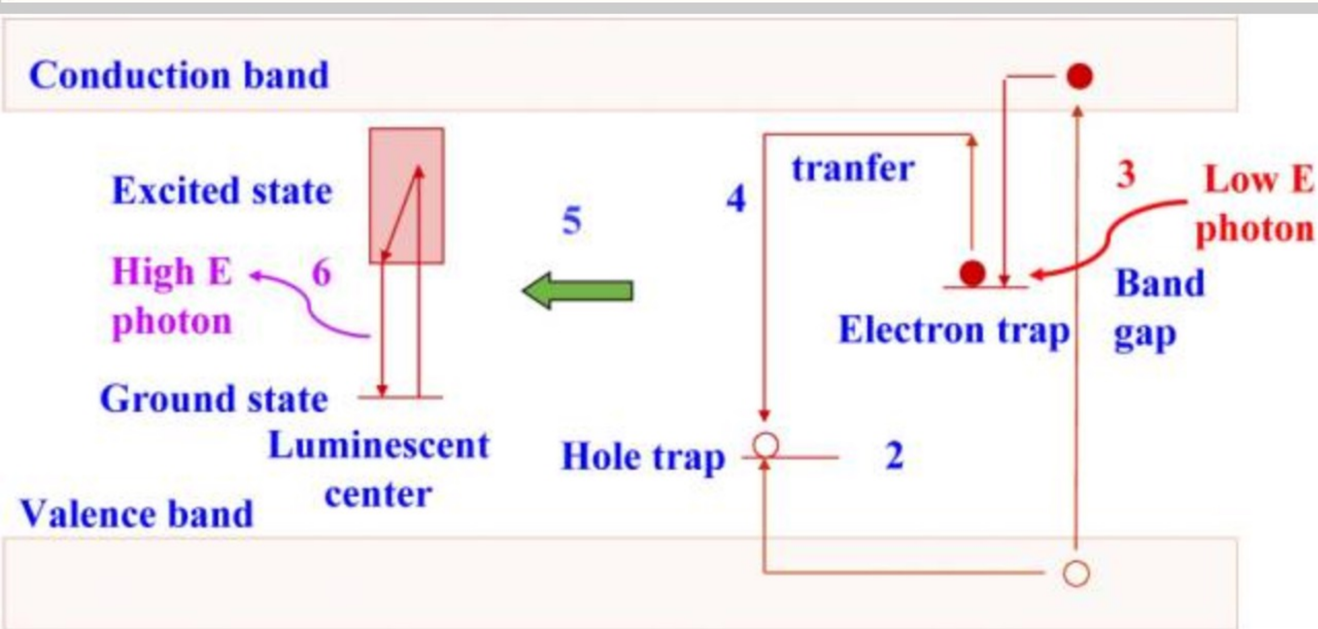
Phosphors

- Some substances absorb radioactivity and emit light. They are called **phosphors**.
- An instrument commonly used to measure the amount of light emitted by a phosphor is a scintillation counter. It converts the light to an electronic response for measurement.
- **Storage phosphors**
  - Can store the energy in a material.
  - Can be released later and give positional information.
  - This is how modern X-rays work. Digitizing spatial information.

Storage Phosphors

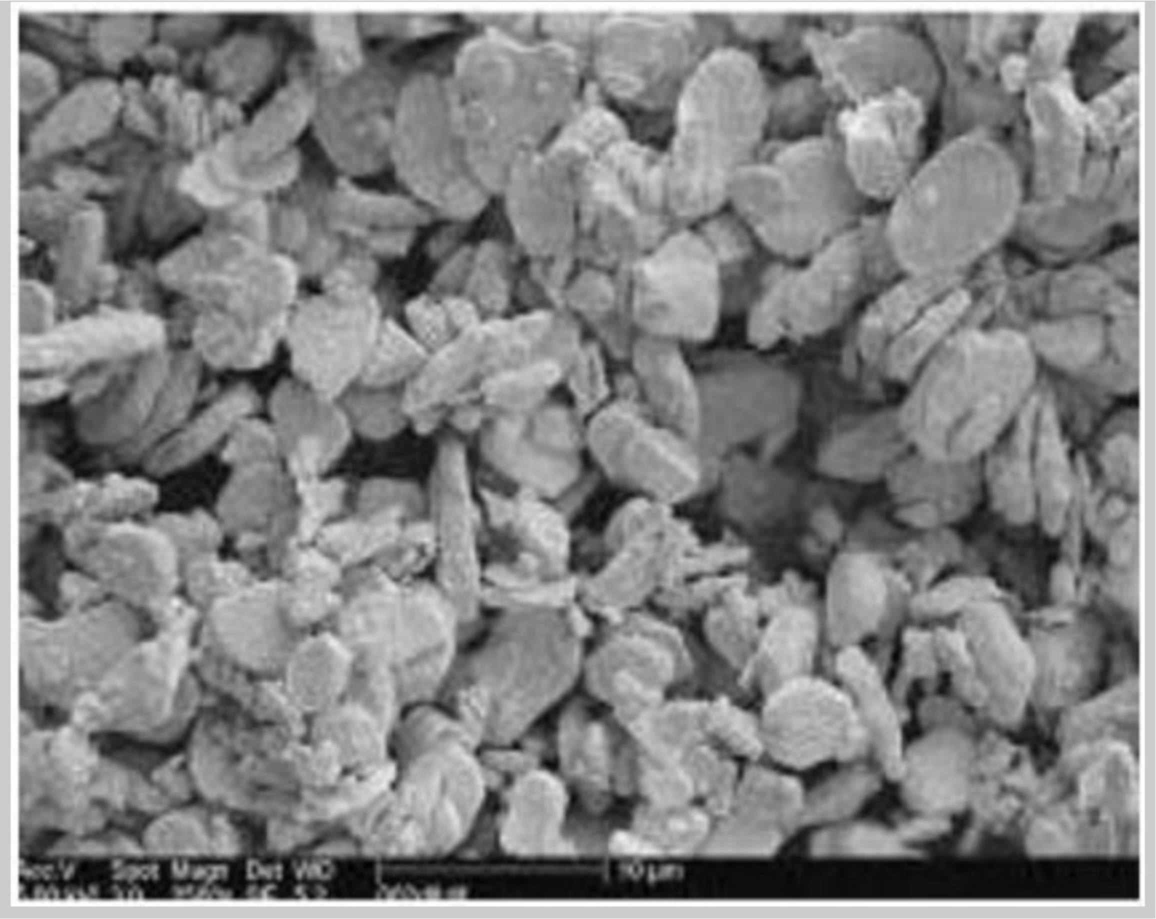


- **Detection:**
  - High energy photon excites electron
  - Ends up in a “trap” energy level.
  - Stays there



- **Readout**
  - Low E photon is absorbed by trapped e⁻
  - Combines with “hole trap”
  - Energy is released as **higher E photon**

Storage Phosphors



- **Material:**
  - Crystals of BaFBr with trace Eu^{2+} substituted for Ba^{2+}.
  - How this material does what it does is still unknown.
  - But it involves electron transfer between atoms.

Radiotracers

- **Radiotracers** are radioisotopes used to study a chemical reaction.
- Radioactive elements are continuously emitting radiation (gamma rays, beta rays, alpha rays etc.)
  - This radiation can be detected:
    - Quantitatively
    - Spatially!
- Radionuclides react chemically exactly the same as nonradioactive nuclei of the same element.

Medical Application of Radiotracers (1 of 2)

- Radiotracers have found wide diagnostic use in medicine.
- Radioisotopes are administered to a patient (usually intravenously) and followed.
- Certain elements collect more in certain tissues, so an organ or tissue type can be studied based on where the radioactivity collects.
- Cancer cells will accumulate more of certain elements than other tissue.

Medical Application of Radiotracers (2 of 2)

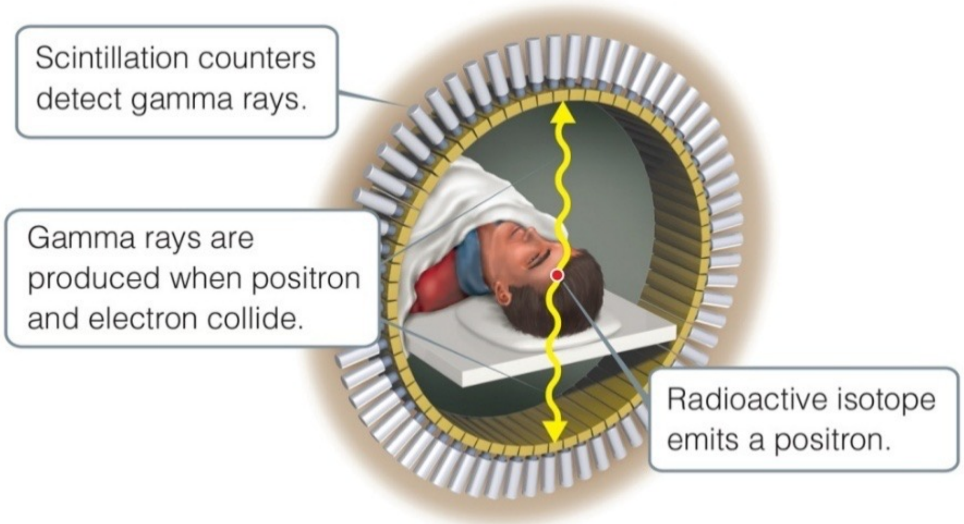
Table 21.6 Some Radionuclides Used as Radiotracers

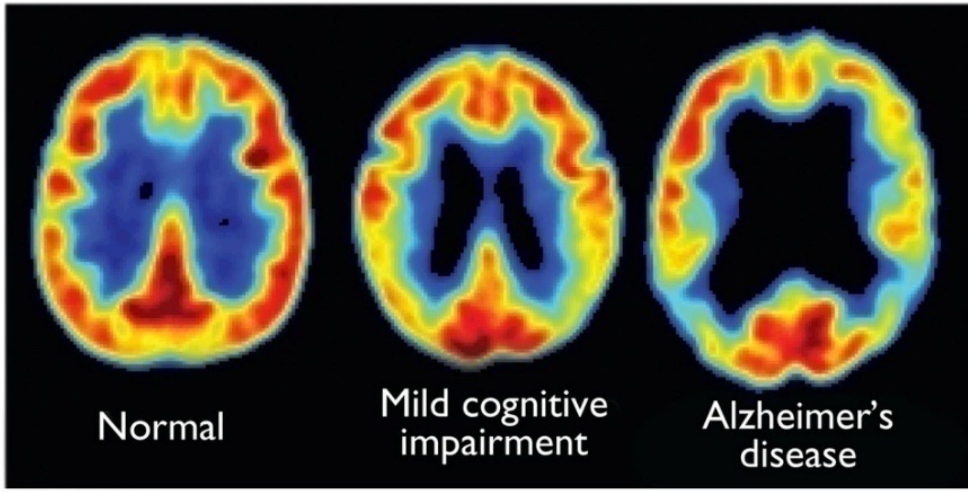
Nuclide	**Half-Life**	**Area of the Body Studied**
Iodine-131	8.04 days	Thyroid
Iron-59	44.5 days	Red blood cells
Phosphorus-32	14.3 days	Eyes, liver, tumors
Technetium-99[a]	6.0 hours	Heart, bones, liver, and lungs
Thallium-201	73 hours	Heart, arteries
Sodium-24	14.8 hours	Circulatory system

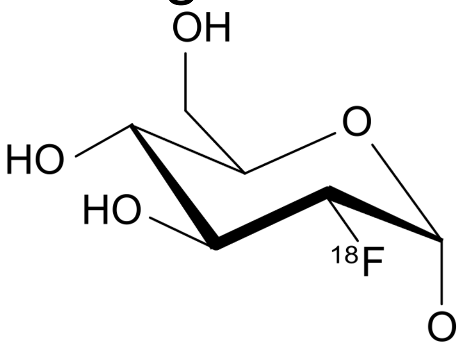
[a] The isotope of technetium is actually a special isotope of Tc-99 called Tc-99*m*, where the *m* indicates a so-called **metastable** isotope.

Positron Emission Tomography (PET Scan)

- A compound labeled with a positron emitter is injected into a patient.
- Blood flow, oxygen and glucose metabolism, and other biological functions can be studied.
- Labeled glucose is used to study the brain, as seen in the figure to the right.







2-Fluoro-2-deoxy-glucose

$${}^{18}_{9}F \rightarrow {}^{0}_{1}\beta + {}^{18}_{8}O$$

21.6 Energy Changes in Nuclear Reactions

- The “glue” that holds nuclei together must be incredibly strong
  - Call “the nuclear strong force”.
  - Energy liberated literally comes from conversion of mass to energy:
  - $E=mc^2$
- Example. What is the mass to energy change for alpha decay of 1 mole of U-238 to Th-234?
  - Mass change = -0.0046 g.

$$\begin{aligned}\Delta E &= (\Delta m)c^2 \\ &= \left(-4.6\times10^{-6}\,\text{kg}\right)\left(3.00\times10^{8}\,\text{m/s}\right)^2 \\ &= -4.1\times10^{11}\ \text{J}\ \left(410\ \text{billion kJ!!}\right)\end{aligned}$$

Mass Defect. What is the mass change from?

- Compare masses of nuclei with masses of the protons and neutrons that make them up.
  - It's always less!
  - That is the ***mass defect.***
- **It's the mass needed to create the energy "glue" that holds the thing together**
- **The "nuclear binding energy"**.

Mass Defect (2 of 2)

Table 21.7 Mass Defects and Binding Energies for Three Nuclei

Nucleus	Mass of Nucleus (amu)	Mass of Individual Nucleons (amu)	Mass Defect (amu)	Binding Energy (J)	Binding Energy per Nucleon (J)
${}^{4}_{2}He$	4.00150	4.03188	0.03038	4.53×10^{-12}	1.13×10^{-12}
${}^{56}_{26}Fe$	55.92068	56.44914	0.52846	7.90×10^{-11}	1.41×10^{-12}
${}^{238}_{92}U$	238.00031	239.93451	1.93420	2.89×10^{-10}	1.21×10^{-12}

Sample Exercise 21.8 Calculating Mass Change in a Nuclear Reaction (1 of 3)

How much energy is lost or gained when 1 mol of cobalt-60 undergoes beta decay, ${}^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\text{e}$? The mass of a ${}^{60}_{27}\text{Co}$ atom is 59.933819 amu, and that of a ${}^{60}_{28}\text{Ni}$ atom is 59.930788 amu.

Solution

The masses include the mass of electrons. Usually their masses don't matter, but here, we are talking tiny changes in mass per atom, so they DO matter.

Must subtract their mass to just have mass of nuclei.

Solve

A ${}^{60}_{27}\text{CO}$ atom has 27 electrons. The mass of an electron is 5.4858×10^{-4} amu.

We subtract the mass of the 27 electrons from the mass of the ${}^{60}_{27}\text{CO}$ atom to fine the mass of the. ${}^{60}_{27}\text{CO}$ nucleus

Sample Exercise 21.8 Calculating Mass Change in a Nuclear Reaction (2 of 3)

$$^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\text{e} \boxed{}$$

$$59.933819 \text{ amu} - (27)(5.4858 \times 10^{-4} \text{amu})$$
$$= 59.919007 \text{ amu (or } 59.919007 \text{ g/mol)}$$

Likewise, for $^{60}_{28}\text{Ni}$, the mass of the nucleus is:

$$59.930788 \text{ amu} - (28)(5.4858 \times 10^{-4} \text{ amu})$$
$$= 59.915428 \text{ amu(or } 59.915428 \text{ g/mol)}$$

The mass change in the nuclear reaction is the total mass of the products minus the mass of the reactant:

$$\Delta m = \text{ mass of electron } + \text{ mass } {}^{60}_{28}\text{Ni nucleus } - \text{ mass of } {}^{60}_{27}\text{Co nucleus}$$
$$= 0.00054858 \text{ amu} + 59.915428 \text{ amu} - 59.919007 \text{ amu}$$
$$= -0.003030 \text{ amu}$$

Thus, when a mole of cobalt-60 decays,

$$\Delta m = -0.003030 \text{ g}$$

Because the mass decreases $(\Delta m < 0)$, energy is released $(\Delta E < 0)$. The quantity of energy released **per mole** of cobalt-60 is calculated using Equation 21.22:

Sample Exercise 21.8 Calculating Mass Change in a Nuclear Reaction (3 of 3)

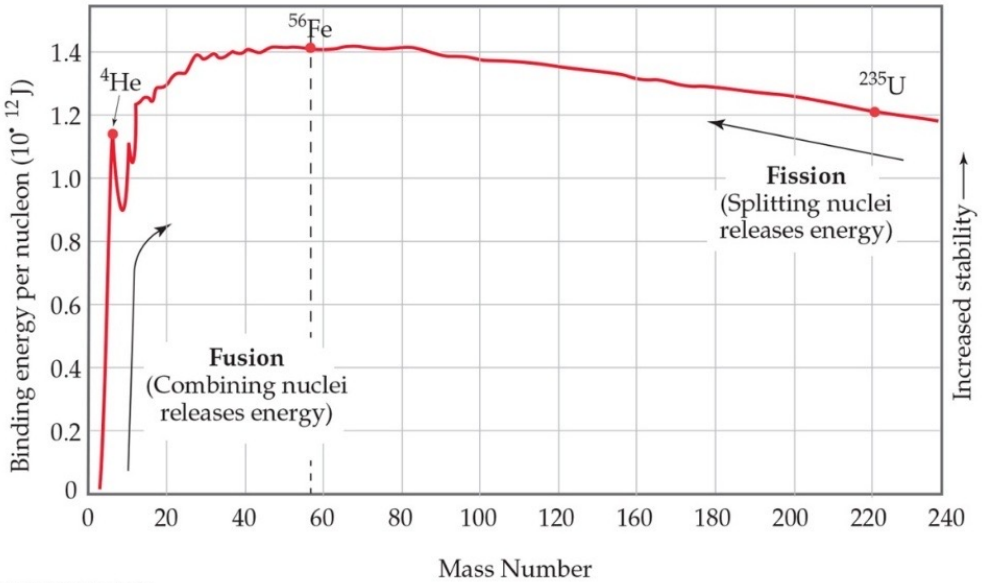
$$\Delta E = c^2 \Delta m$$

$$= (2.9979 \times 10^8 \text{ m/s})^2 (-0.003030 \cancel{\text{g}}) \left(\frac{1 \text{ kg}}{1000 \cancel{\text{g}}} \right)$$

$$= -2.723 \times 10^{11} \frac{\text{kg} - \text{m}^2}{\text{s}^2} = -2.723 \times 10^{11} \text{ J}$$

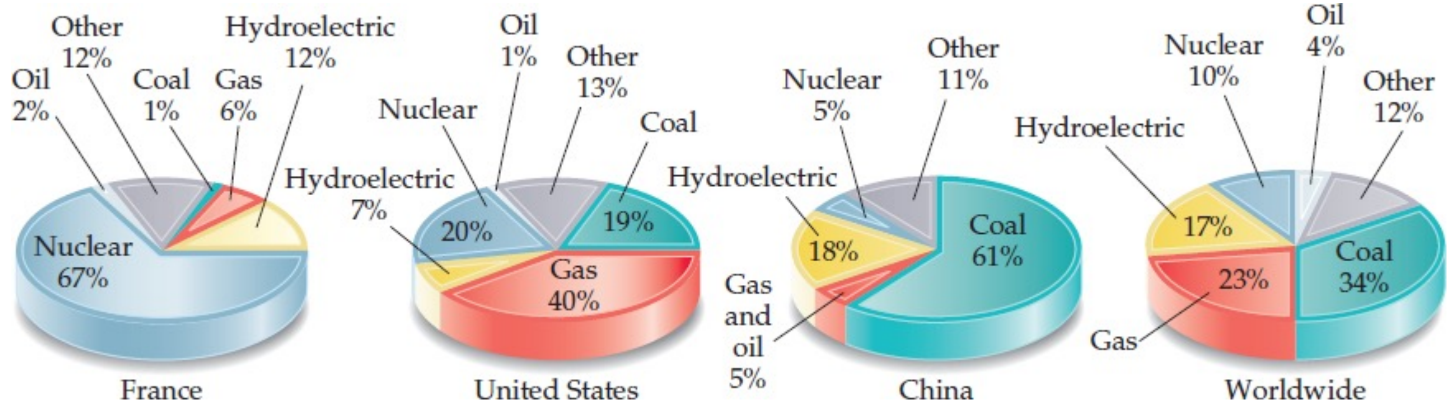
Effects of Nuclear Binding Energy on Nuclear Processes

- Dividing the binding energy by the number of nucleons gives values that can be compared.
- Heavy nuclei gain stability and give off energy when they split into two smaller nuclei. This is **fission**.
- Lighter nuclei emit great amounts of energy by being combined in **fusion**.



Energy: Chemical Vs Nuclear

- Chemical energy is associated with making and breaking chemical bonds. B.E. on the order of **10^3 Joules/mole.**
- Nuclear energy is enormous in comparison. **10^{11}-10^{12} Joules/mole**
- Nuclear energy is due to changes in the nucleus of atoms changing them into different atoms.
- 10% of worldwide energy comes from nuclear energy.

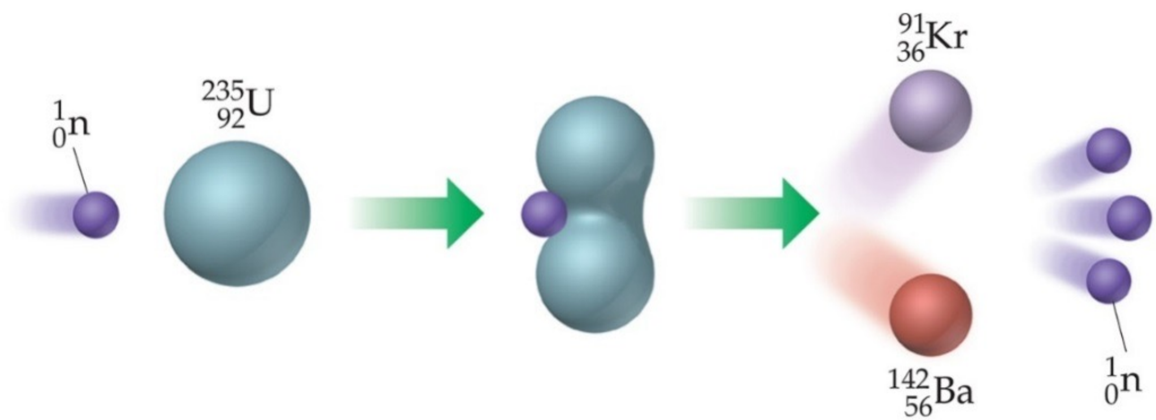


21.7 Nuclear Power: Fission (1 of 3)

- Commercial nuclear power plants use fission.
- Heavy nuclei can split in many ways. The equations below show two ways U-235 can split after bombardment with a neutron.

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{137}_{52}\mathrm{Te} + {}^{97}_{40}\mathrm{Zr} + 2\,{}^{1}_{0}\mathrm{n} \qquad [21.24] $$

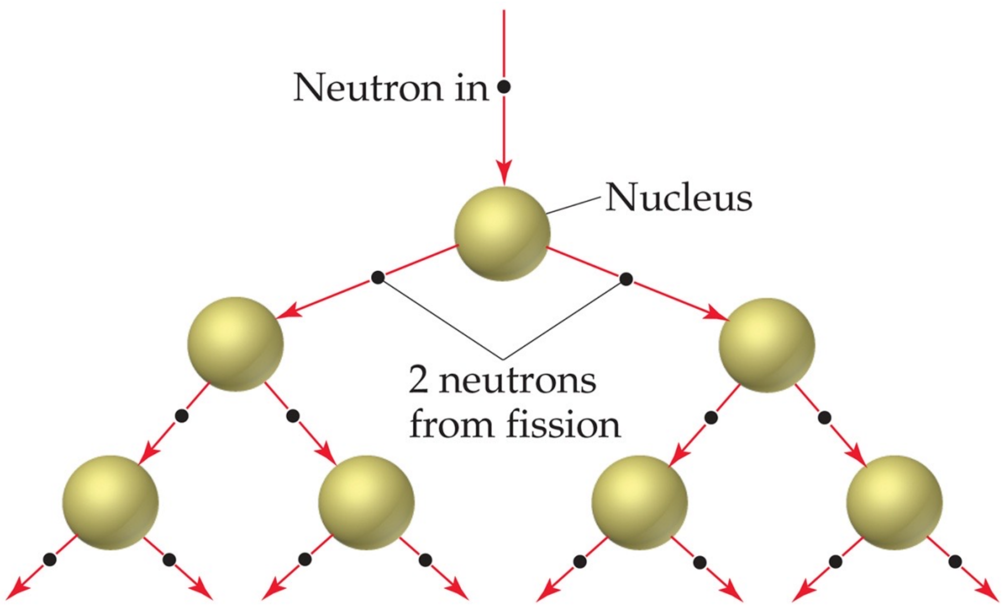
$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} \qquad [21.25] $$



Note: For every 1 neutron used, 3 are produced

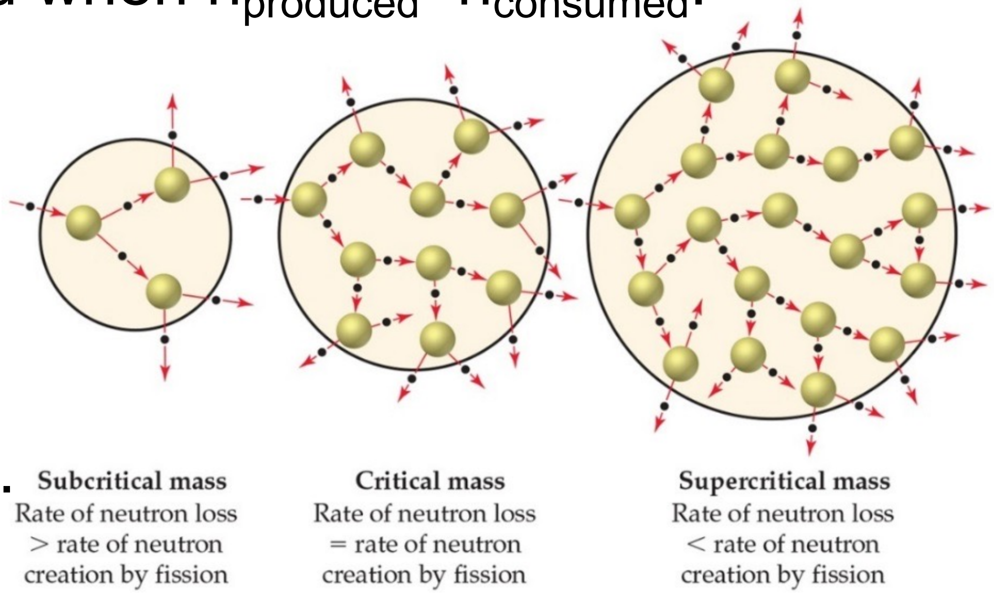
21.7 Nuclear Power: Fission (2 of 3)

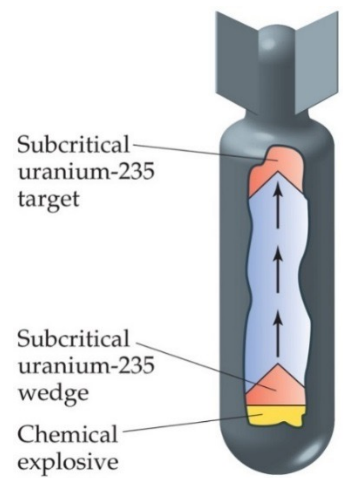
- Neutrons released in the transmutation
- A **chain reaction results**.



21.7 Nuclear Power: Fission (3 of 3)

- **But:** every neutron produced does not contact another nucleus.
  - Amount of stuff needed when $n_{produced} = n_{consumed}$:
    - **critical mass**.
- When $n_{produced} > n_{consumed}$
  - **supercritical mass**
  - Chain reaction.
  - an explosion will occur.
  - A nuclear weapon.



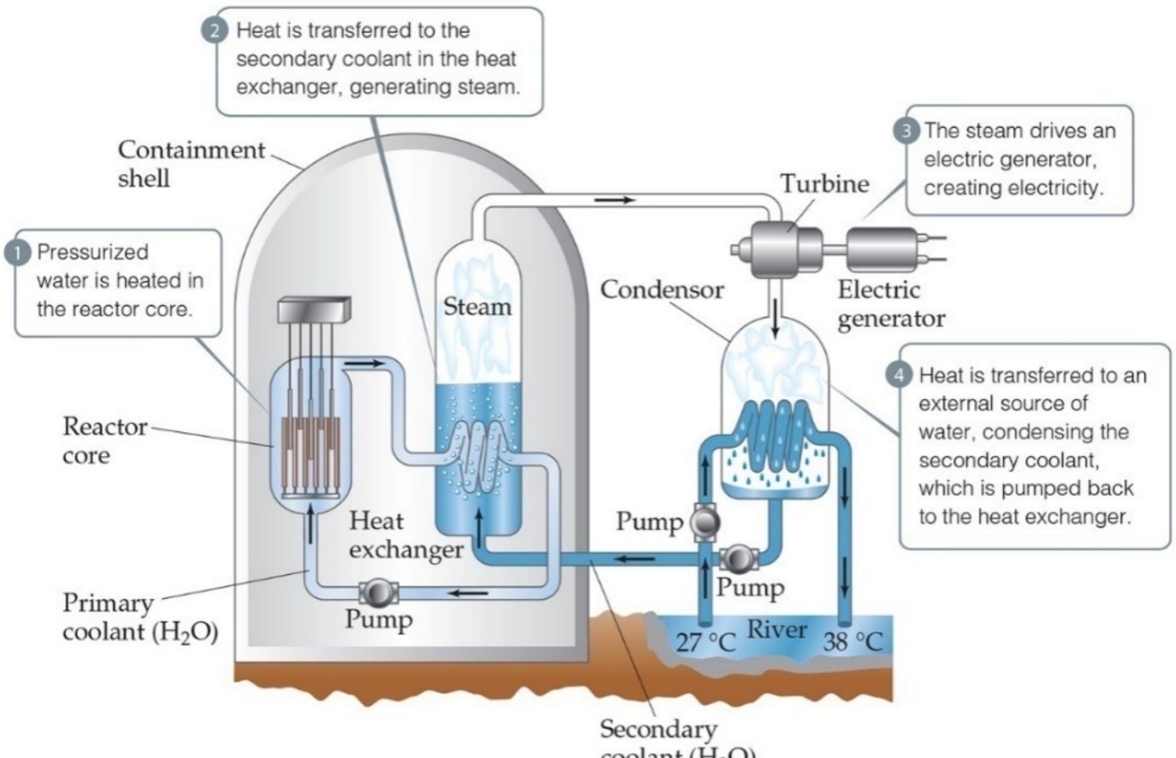


Nuclear Reactors (1 of 2)

Nuclear reaction produces **heat**

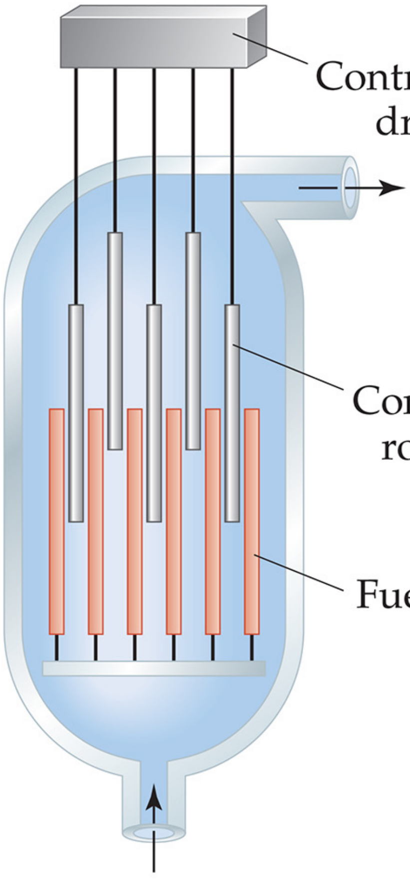
Heat produces steam

Steam turns tubine (just like a gas or coal plant).



Nuclear Reactors (2 of 2)

- **The reactor core**
  - fuel rods (Uranium
    - Only 3-5% ^{235}U
  - control rods,
    - Neutron absorbers
      - graphite,
  - coolant.
- The control rods
  - absorb some neutrons
  - Keeps from getting too hot
  - Meltdown: When T is higher than melting point of fuel



Nuclear Waste

- When there is not enough ^{235}U left to maintain reaction to produce power.
  - Spent fuel, but still very radioactive!
  - Stored in giant pools of water on site.
  - Will stay radioactive for thousands of years.
- Political opposition to both:
  - storage site location
  - Transportation.
- Massive safety challenges for reprocessing.

21.7 Nuclear Power: Fusion

- Small nuclei can fuse.
  - thermonuclear reactions.
- Enormous amounts of energy

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

- 1×10^{11} J/mole
- 5 g/mole fuel.
- 0.2×10^{11} J/g

- Compare to methane:
  - Heat of combustion: -890×10^{3} J/mole
  - 890×10^{3} J/mole(mole/16 g) = 55.6 kJ/g.
  - 0.2×10^{11} J/g fusion)/55.6 kJ/g = 3.6×10^{5} g methane/g fusion fuel!

21.7 Nuclear Power: Fusion

- Small nuclei can fuse.
  - thermonuclear reactions.
- Enormous amounts of energy

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

- 1×10^{11} J/mole
- 5 g/mole fuel.
- 0.2×10^{11} J/g

- Produces no radioactive bi-products.
- *But you have to squeeze the together!*
  - Very high T and pressure.
- Hydrogen atomic bombs
  - Require a fission nuclear explosion to make it happen.
  - Outside the gravity of a star, this is very hard.

21.9 Radiation in the Environment and Living Systems

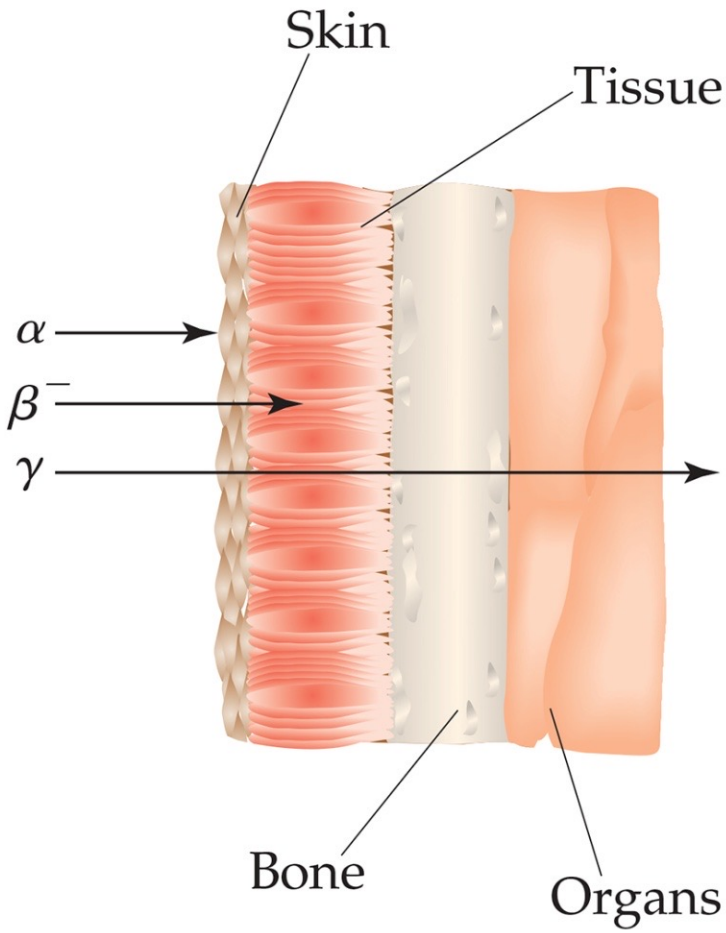
- We are constantly exposed to radiation.
- **Ionizing radiation:**
  - **Radiation that produces ions and radicals**
  - Radical: compound with an unpaired electron.
- Most common reaction caused by radioactivity:

$$H_2O \xrightarrow{\text{Ionizing radiation}} e^-_{aq}, HO\cdot, H\cdot, HO_2\cdot, H_3O^+, OH^-, H_2O_2, H_2$$

- Because living things are 70% water.
- It's the most likely molecule to get hit
- OH radicals very reactive
- React with anything, proteins, DNA, RNA, everything.

Damage to Cells

- Damage to tissue depends on:
  - the type of radioactivity
    - Alpha, beta gamma
    - Amount of exposure,
    - Location. inside or outside the body.
- Outside the body, gamma rays are most dangerous.
  - Other radiation mostly stops at skin
- Inside the body,
  - alpha radiation is the worst.



Exposure (1 of 2)

- We are constantly exposed to radiation. What amount is safe?
- Setting standards for safety is difficult.
- Low-level, long-term exposure can cause health issues.
- Damage to the growth-regulation mechanism of cells results in cancer.

Exposure (2 of 2)

Table 21.8 Average Abundances and Activities of Natural Radionuclides †

	Potassium-40	Rubidium-87	Thorium-232	Utanium-238
Land elemental abundance (ppm)	28,000	112	10.7	2.8
Land activity (Bq/kg)	870	102	43	35
Ocean elemental concentration (mg/L)	339	0.12	1×10^{-7}	0.0032
Ocean activity (Bq/L)	12	0.11	4×10^{-7}	0.040
Ocean sediments elemental abundance (ppm)	17,000		5.0	1.0
Ocean sediments activity (Bq/kg)	500		20	12
Human body activity (Bq)	4000	600	0.08	0.4‡

† Data from "Ionizing Radiation Exposure of the Population of the United States," Report 93, 19 87, and Report 160, 2009, National Council on Radiation Protection.

‡ Includes lead-210 and polonium-210. daughter nuclei of uranium-238.

Radiation Dose

- Two units are commonly used to measure exposure to radiation:
  - **Gray (Gy)**: absorption of 1 J/kg of tissue **(a lot!)**
  - **Rad (for radiation absorbed dose)**: absorption of 0.01 J/kg of tissue (**100 rad = 1 Gy**)
- Not all forms of radiation harm tissue equally.
  - A **relative biological effectiveness (RBE)** is used to show how much biological effect there is.
    - A fudge factor for badness.

Short-Term Exposure (1 of 2)

- The effective dose is called the **rem**

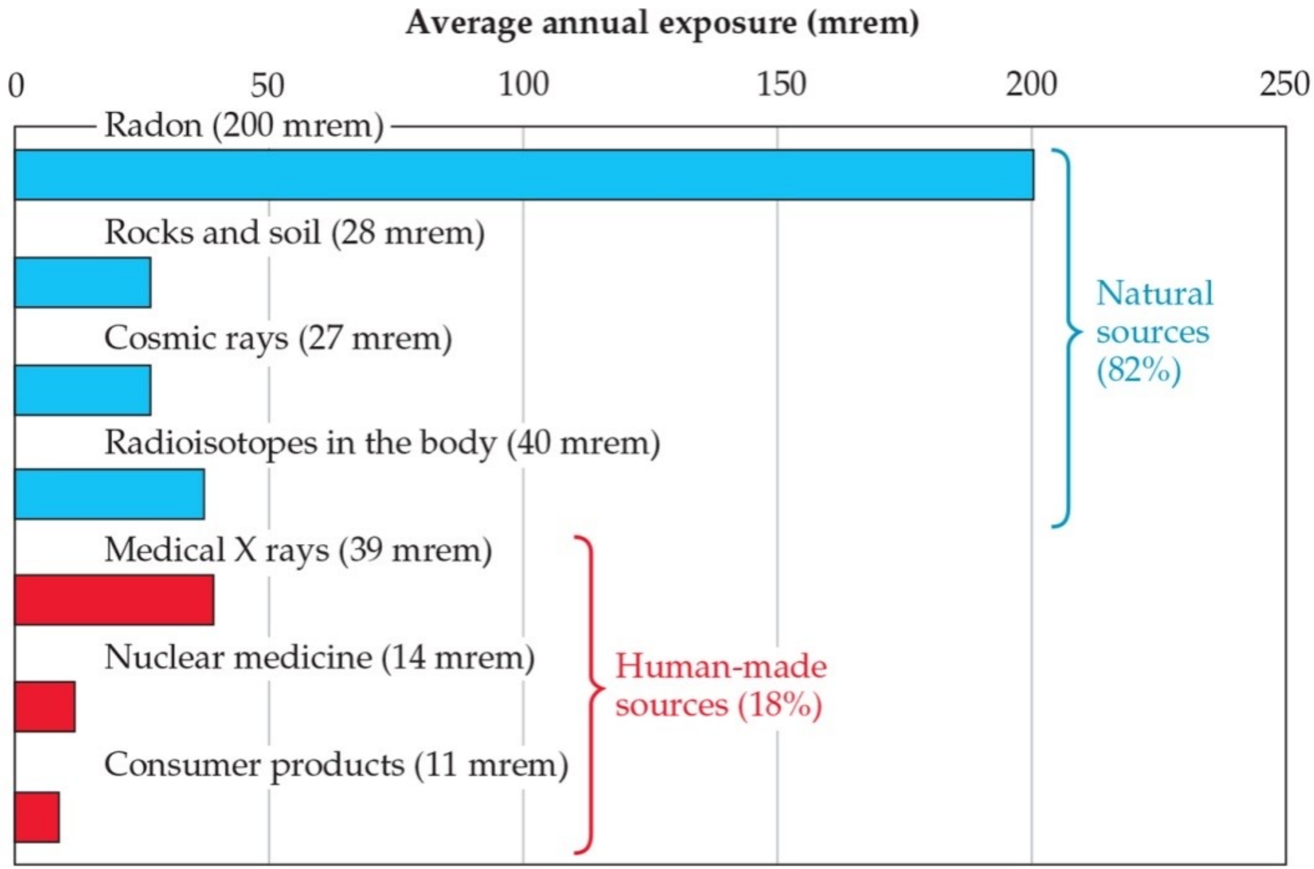
$$\#\ \text{of rem} = (\#\ \text{of rad})(\text{RBE})$$

- Average exposure to a person per year due to all natural sources of ionizing radiation is about 360 mrem.

Table 21.9 Effects of Short-Term Exposures to Radiation

Dose (rem)	Effect
0-25	No detectable clinical effects
25-50	Slight, temporary decrease In white blood cell counts
100-200	Nausea; marked decrease in white blood cell counts
500	Death of half the exposed population within 30 days

Short-Term Exposure (2 of 2)



Chapter 17: Buffers!
The Henderson-Hasselback Equation
The equation of buffers

$$\mathrm{pH} = \mathrm{p}K_a + \log\left(\frac{[\mathrm{A}^-]}{[\mathrm{HA}]}\right)$$

Example: Using the Henderson–Hasselback Equation to Find pH

- What is the pH of a buffer that is 0.12 *M* in lactic acid, $CH_3CH(OH)COOH$, and 0.10 *M* in sodium lactate?

K_a for lactic acid is 1.4×10^{-4}.

$$-\mathrm{pH} = \mathrm{p}K_a + \log\left(\frac{[\mathrm{A}^-]}{[\mathrm{HA}]}\right)$$

$$= -\log(1.4 \times 10^{-4}) + \log\left[\frac{(0.10\ M)}{(0.12\ M)}\right]$$

$$= 3.85 + (-0.08) = 3.77$$

Example of pH Calculation for Buffer after Strong Base Addition (1 of 2)

- A buffer is made by adding $0.300 \text{ mol } HC_2H_3O_2$ and $0.300 \text{ mol } NaC_2H_3O_2$ to enough water to make 1.00 L. 0.020 mol of NaOH is added. What's the pH?

1) Stoichiometry table – limiting reactant calculation

$$CH_3COOH(aq) + OH^-(aq) \rightarrow H_2O(l) + CH_3COO^-(aq)$$

Before reaction (mol)	0.300	0.020	-	0.300
Change (limiting reactant) (mol)	–0.020	–0.020	-	+0.020
After reaction (mol)	0.280	0	-	0.320

Example of pH Calculation for Buffer after Strong Base Addition (2 of 2)

2) Henderson–Hasselbalch equation:

$$\text{pH} = \text{p}K_a + \log\left(\frac{[\text{A}^-]}{[\text{HA}]}\right)$$

HA and A^- are in the same solution,

volume for each is the same

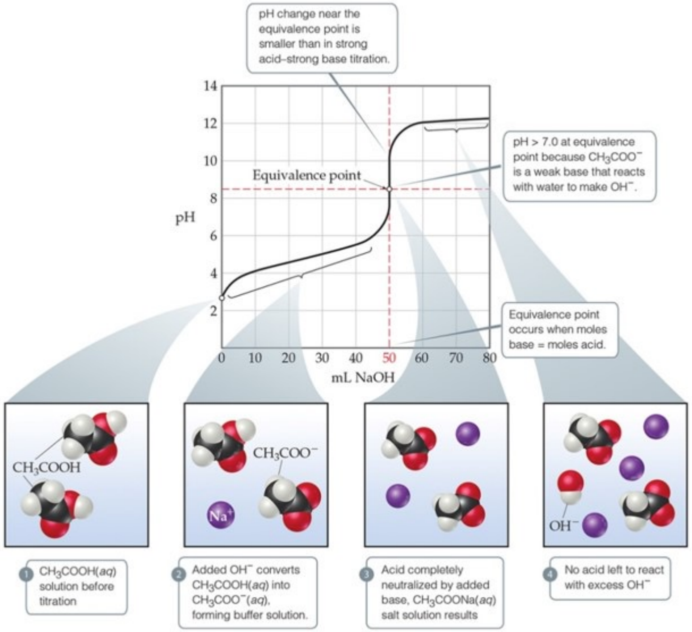
molarity ratio = moles ratio

$$\text{pH} = \text{p}K_a + \log\left(\frac{n_{HA}}{n_{A^-}}\right) \qquad \text{pH} = 4.74 + \log\left(\frac{0.320}{0.280}\right) = 4.80$$

Titration of a Weak Acid with a Strong Base

- four distinct regions:

1. Initial pH uses K_a calculation.
2. Between initial pH and equivalence point (excess acid) uses limiting reactant then Henderson-Hasselback.
3. At the equivalence point.
4. After the equivalence point (excess strong base).



17.4 Solubility Equilibria

- Many Ionic compounds are not very soluble in water.

- The equilibrium constant expression is called the **solubility-product constant**. It is represented as
- K_{sp}
- $Ba_3(PO_4)(s) \rightleftharpoons 3Ba^{2+}(aq) + 2PO_4^{-3}(aq)$

$$K_{sp} = \left[Ba^{2+}\right]^3 \left[PO_4^{\ 3-}\right]^2$$

Calculating Solubility with a Common Ion (1 of 2)

- What is the molar solubility CaF_2 in $0.010\ M\ Ca(NO_3)_2$?

1) $CaF_2(s) \rightleftharpoons Ca^{2+}(aq) + 2F^-(aq)$

2) $K_{sp} = [Ca^{2+}][F^-]^2 = 3.9 \times 10^{-11}$

3)

$$CaF_2(s) \rightleftharpoons Ca^{2+}(aq) + 2F^-(aq)$$

Initial concentration (M)	-	0.010	0
Change (M)	-	$+x$	$+2x$
Equilibrium concentration (M)	-	$(0.010 + x)$	$2x$

Chapter 20, Electrochemistry.

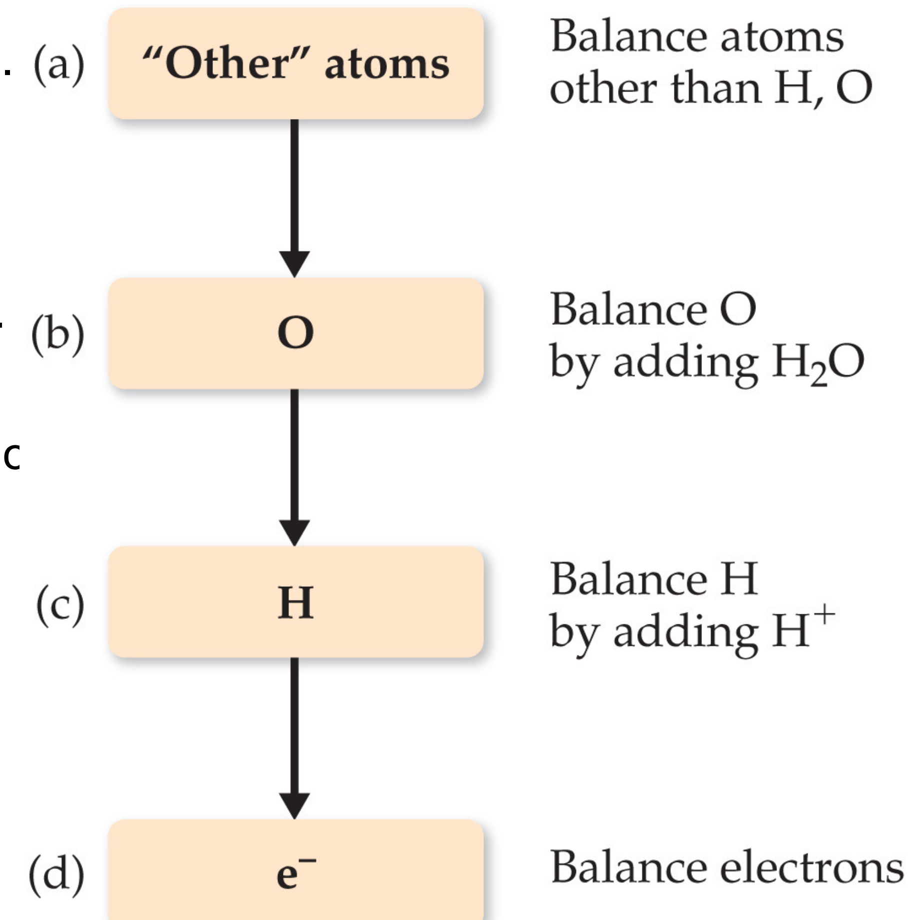
1. Assigning oxidation numbers

First step: Where to the electrons come from?
Where do they go?
Must Assign Oxidation Numbers (as a Reminder)

1. **Elements** (pure substance) = 0
2. Monatomic ion = charge
3. **F: –1**
4. **O: –2** (unless peroxide = –1)
5. **H: +1** (unless a metal hydride = –1)
6. The **sum** of the oxidation numbers **equals** the overall **charge** (0 in a compound).

Balancing Redox Equations: The Half-Reaction Method

1) Make two half-reactions (oxidation and reduction).
2) Balance elements **other** than O and H.
3) Balance O and H using H_2O/H^+.
4) Add **electrons** to balance **charges.**
5) Multiply by common factor to make electrons ***in each half-reaction*** equal.
6) **Add** the half-reactions.
7) Simplify by dividing by common factor c converting H^+ to OH^- if basic.
8) Double-check:
    1) Element balance
    2) charge balance!

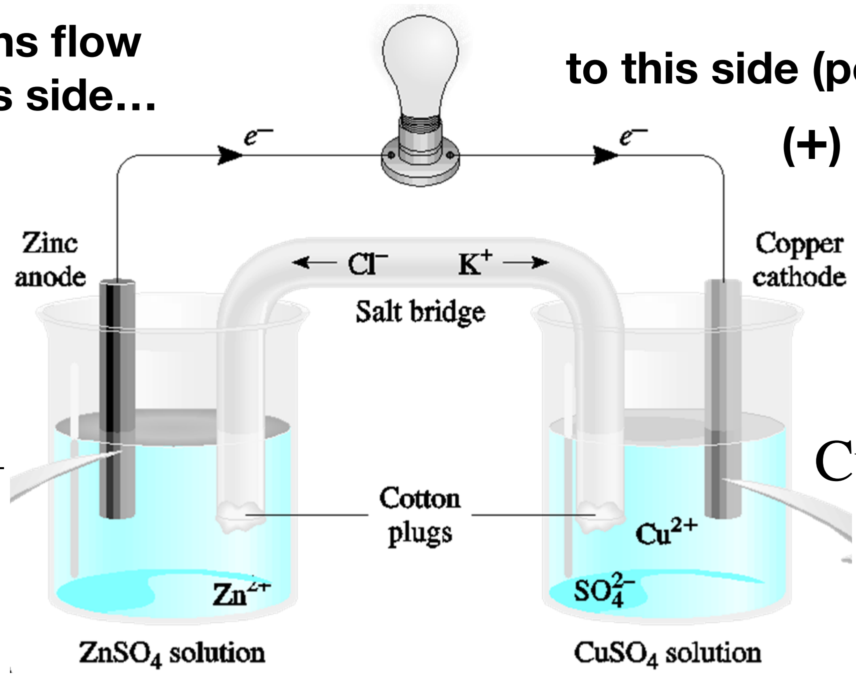


Galvanic Cell.

But what if you **SEPARATED** the two half reactions?
Electrons then run through a wire from one half reaction to the other.
A setup like this is called an **ELECTROCHEMICAL CELL**.

electrons flow from this side… (–)

to this side (positive)! (+)



OXIDATION SIDE:

$$Zn_{(s)} \rightleftharpoons Zn^{2+}_{(aq)} + 2e^-$$

REDUCTION SIDE:

$$Cu^{2+}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$$

ANODE
the half side of a cell where
the OXIDATION occurs

BRIDGE
allows ions to flow
to close the circuit
(each side must remain
electrically neutral)

CATHODE
the half side of a cell where
the REDUCTION occurs

Calculate Standard Cell Potentials

Therefore: the total potential is the DIFFERENCE of the reduction potentials between the cathode and the anode (always "Reduction" part first):

$$E^{o}_{tot} = E^{o}_{red}\begin{pmatrix} cathode \\ reduction \end{pmatrix} + E^{o}_{ox}\begin{pmatrix} anode \\ oxidation \end{pmatrix}$$

$$\boxed{E^{o}_{tot} = E^{o}_{red}\begin{pmatrix} cathode \\ oxidation \end{pmatrix} - E^{o}_{red}\begin{pmatrix} anode \\ reduction \end{pmatrix}}$$

ex: Daniell Cell

$$\underbrace{\mathrm{Zn}_{(s)}\big|\mathrm{Zn}^{2+}_{(aq)}}_{\text{anode half-cell}} \;\|\; \underbrace{\mathrm{Cu}^{2+}_{(aq)}\big|\mathrm{Cu}_{(s)}}_{\text{cathode half-cell}}$$

$$\begin{array}{rl} & E^{o}_{red}\left(\mathrm{Cu}^{2+}/\mathrm{Cu}\right) = 0.34\ \mathrm{V}\ vs.\ \mathrm{SHE} \\ - & E^{o}_{red}\left(\mathrm{Zn}^{2+}/\mathrm{Zn}\right) = -0.76\ \mathrm{V}\ vs.\ \mathrm{SHE} \\ \hline & E^{o}_{tot} = 1.10\ \mathrm{V}\ vs.\ \mathrm{SHE} \end{array}$$

Calculations using The Nernst Equation

All the relationships that we derived only applies under standard conditions.

-All reactants at **1 M** concentration
-T=**298 K**.
-Gases all at **1 atm**.

Why? Because we are using the Standard Reduction Potential:

$$-nFE^{\circ} = -RT\ln K$$

And those are all at standard conditions.

What happens if the reaction is not under "**standard conditions**"?
What if the concentrations of the solutions are **not** all **1 M**?

NERNST EQUATION: The equation that gives the potential under non-standard conditions

Q = reaction quotient

$$Q = \frac{[\text{products}]}{[\text{reactants}]}$$

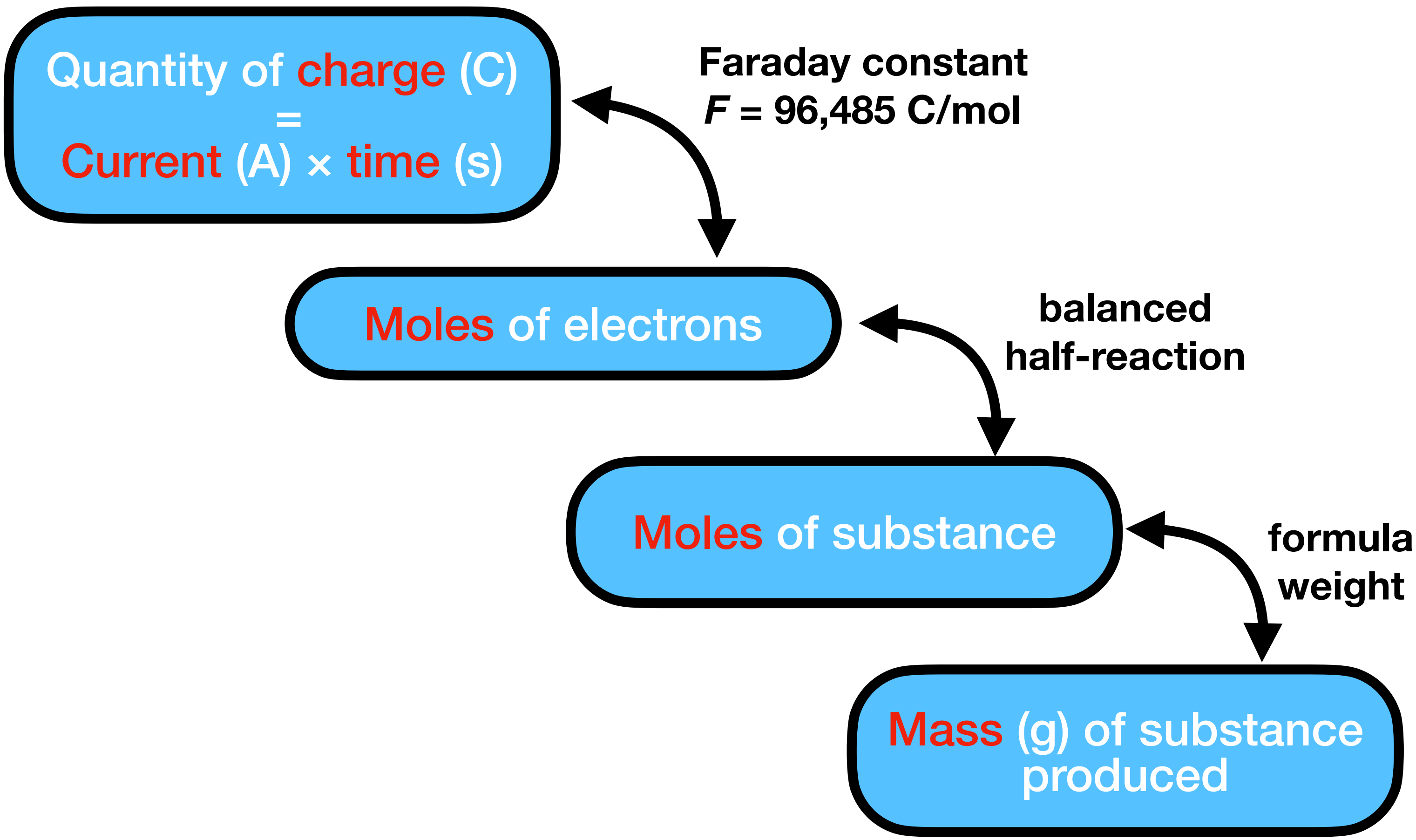
$$E = E^{\circ} - \frac{RT}{nF}\ln Q$$

potential under
any conditions

potential under

specific concentrations used

Using Faraday's Law
To calculate moles of electrons
Etc.



Chapter 21, Nuclear Chemistry
1. Properties of Radioactive Decay

Three types:

Alpha (α)
Beta (β)
Gamma (γ)

Table 21.1 Properties of Alpha, Beta, and Gamma Radiation

Property	α	β	γ
Charge	2+	1−	0
Mass	6.64×10^{-24} g	9.11×10^{-28} g	0
Relative penetrating power	1	100	10,000
Nature of radiation	$^{4}_{2}He$ nuclei	Electrons	High-energy photons

Balancing nuclear equations
1 charge
2 mass

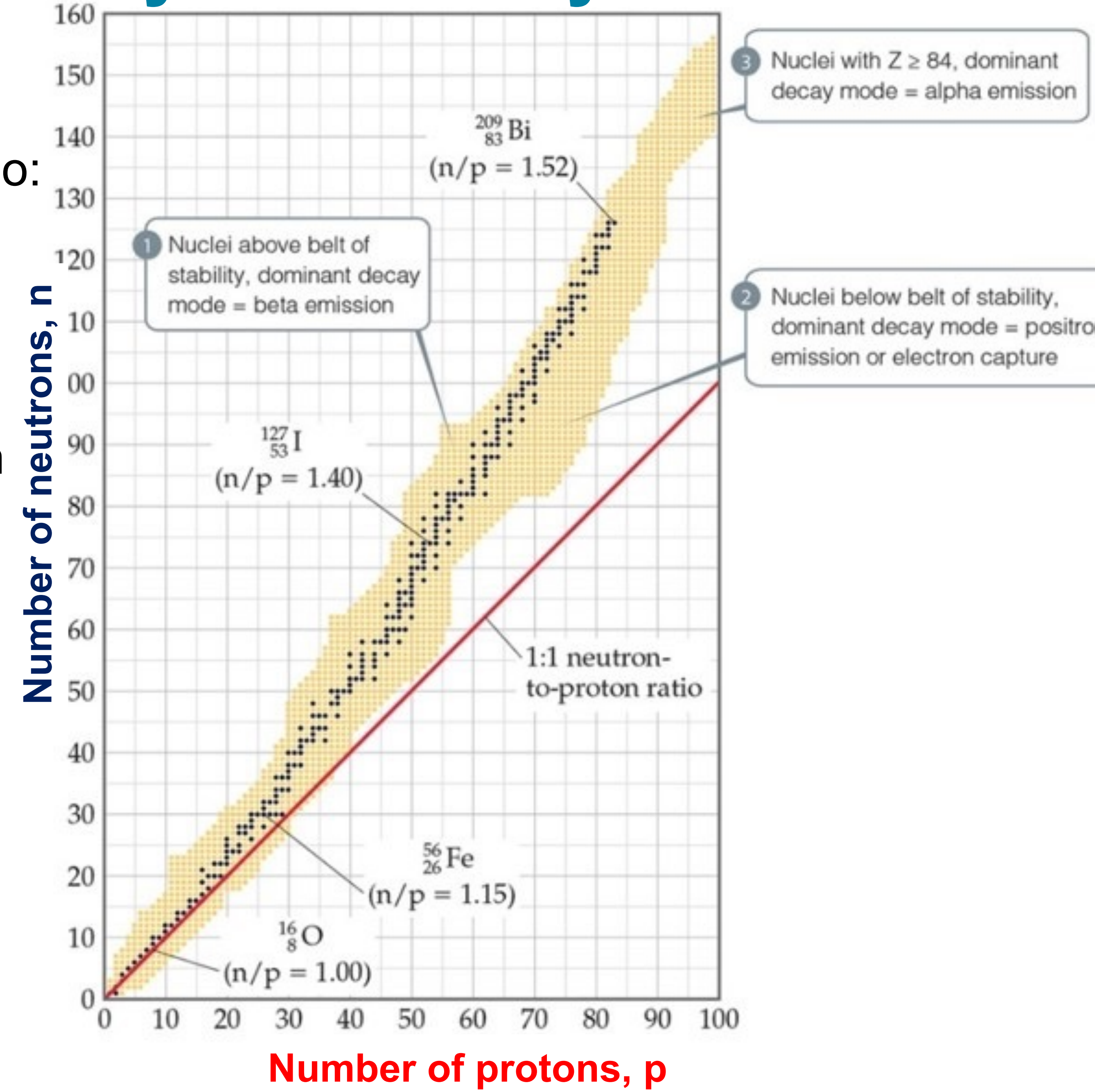
Table 21.3 Types of Radioactive Decay

Type	Nuclear Equation	Change in Atomic Number	Change in Mass Number
Alpha emission	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	–2	–4
Beta emission	${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}e$	+1	Unchanged
Positron emission	${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}^{0}_{+1}e$	–1	Unchanged
Electron capture*	${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}_{Z-1}^{A}Y$	–1	Unchanged

*The electron captured comes from the electron cloud surrounding the nucleus.

Valley of Stability

- Smaller nuclei
- Proton/neutron ratio: **1:1**
- Larger nuclei:
  - More **protons**
  - More repulsion
  - Need **more Neutrons.**
- **belt of stability.**
- **Zone of stability**
  - It shows which nuclides would be stable.



Example problem: transmutation

- **Write the nuclear reaction from this short form**

$$^{27}_{13}\text{Al}(\text{n}, \alpha)^{24}_{11}\text{Na}.$$

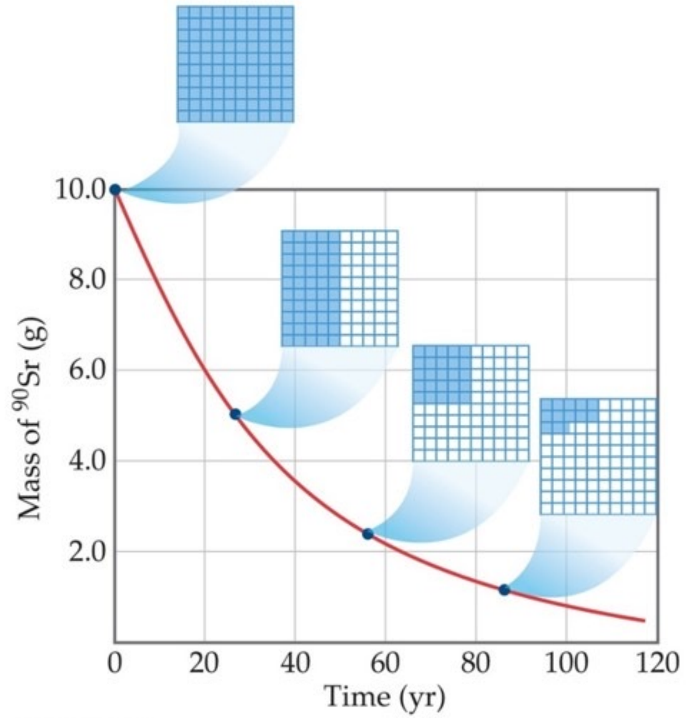
- $^{27}_{13}Al + n \rightarrow\ ^{24}_{11}Al + \ ^{4}_{2}He$

21.4 Kinetics of Radioactive Decay Example:

The half-life of cobalt-60 is 5.27 yr.

How much of a 1.000-mg sample of cobalt-60 is left after 15.81 yr?

- $ln\frac{N_t}{N_0} = -kt$
- $e^{-kt} = \frac{N_t}{N_0}$
- $ln\frac{0.5}{1} = -kt_{\frac{1}{2}} = -.693$
- $\frac{0.693}{t_{1/2}} = k$
- $\frac{0.693}{5.27yr} = k = 0.1315yr^{-1}$
- $N_0\ e^{-kt} = N_t = (1mg)e^{-(0.1315yr^{-1})15.81yr} = 0.125\,mg$



Mass Defect

Table 21.7 Mass Defects and Binding Energies for Three Nuclei

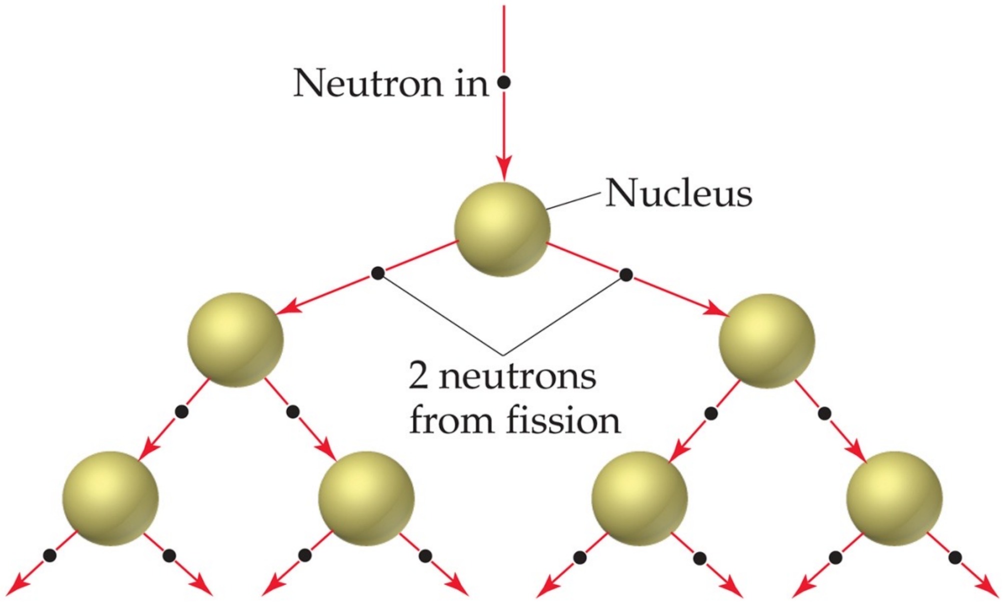
Nucleus	Mass of Nucleus (amu)	Mass of Individual Nucleons (amu)	Mass Defect (amu)	Binding Energy (J)	Binding Energy per Nucleon (J)
${}^{4}_{2}\text{He}$	4.00150	4.03188	0.03038	4.53×10^{-12}	1.13×10^{-12}
${}^{56}_{26}\text{Fe}$	55.92068	56.44914	0.52846	7.90×10^{-11}	1.41×10^{-12}
${}^{238}_{92}\text{U}$	238.00031	239.93451	1.93420	2.89×10^{-10}	1.21×10^{-12}

- What is the mass to energy change for alpha decay of 1 mole of U-238 to Th-234?
  - Mass change = -0.0046 g.

$$
\begin{aligned}
\Delta E &= (\Delta m)c^2 \\
&= \left(-4.6 \times 10^{-6}\,\text{kg}\right)\left(3.00 \times 10^{8}\,\text{m/s}\right)^2 \\
&= -4.1 \times 10^{11}\ \text{J}\ \left(410\ \text{billion kJ!!}\right)
\end{aligned}
$$

21.7 Nuclear Power: Fission (2 of 3)

- Neutrons released in the transmutation
- A **chain reaction results**.



Exam 3. The breakdown

• Buffers/titration:	I	Balancing nuclear reactions	I
• Make a buffer	I	Kinetics of nuclear decay	I
• Appropriate buffers	I	Stable/unstable nuclei/zone	I
• Ksp		II	
• Categorizing redox reactions		I	
• Balancing by half reaction		I	
• Calculating std. cell potential		II	
• Nernst equation		II	
• Faradays' law electrolysis		I	
• Nuclear Energy release		I	
• Nuclear decay pathways		I	
• Nuclear energy		I	