Chapter 22

Nuclear Chemistry

Chemistry by Whitten, Davis, Peck, and Stanley, 10th edition (2014)

Chemical vs. Nuclear Reactions

- In chemical reactions, atoms rearrange to produce new substances.
  - only electrons participate
  - nuclei are unchanged
  - *Law of Conservation of Mass* is upheld
- In nuclear reactions, unstable atomic nuclei break down (= *decay*) into smaller, more stable nuclei.
  - *Law of Conservation of Mass* is violated
  - a tiny amount of mass is transformed into a huge amount of energy ($E = mc^2$)!

Review: Isotopes

- *Isotopes* = atoms of the same element that have a <u>different</u> number of *neutrons*

A = *mass number* (always an integer)

= # of protons + # of neutrons

= # p + # n

There are <u>two</u> formats for representing an isotope:

Format 1: element name-*A* (or E-*A*)

Format 2:

$$\begin{array}{ll}\text{mass \#} \longrightarrow & A \\ \text{atomic \#} \longrightarrow & Z\end{array}\;\mathrm{E}$$

Review: Isotopes (cont.)

- Neon has three natural, stable isotopes:

Ne-20, Ne-21, and Ne-22

mass # → 20
atomic # → 10

$^{20}_{10}\text{Ne}$ # neutrons = $A - Z$ = 20 – 10 = 10

mass # → 21
atomic # → 10

$^{21}_{10}\text{Ne}$ # neutrons = $A - Z$ = 21 – 10 = 11

mass # → 22
atomic # → 10

$^{22}_{10}\text{Ne}$ # neutrons = $A - Z$ = 22 – 10 = 12

Nuclides

- *Nuclides* = different atomic forms of ALL elements (not just one), with focus on the composition of the nuclei
- Nuclides are represented by the *nuclide symbol* shown below:

$$^{A}_{Z}\mathrm{E}$$

Nuclear Stability, Mass Deficiency, and Nuclear Binding Energy

Nuclear Stability

- *Radioactivity* = the tendency of an *unstable* nucleus to emit radiation

- All elements with $Z \leq 83$ (bismuth) have at least one *stable* isotope.

- What makes a nucleus "stable"? Here are some criteria:
  - for light elements ($Z < 20$): $N / Z = 1$

    where N = # of neutrons, Z = # of protons
  - for heavier elements: $1 < N / Z \leq 1.6$
  - even numbers of both protons and neutrons

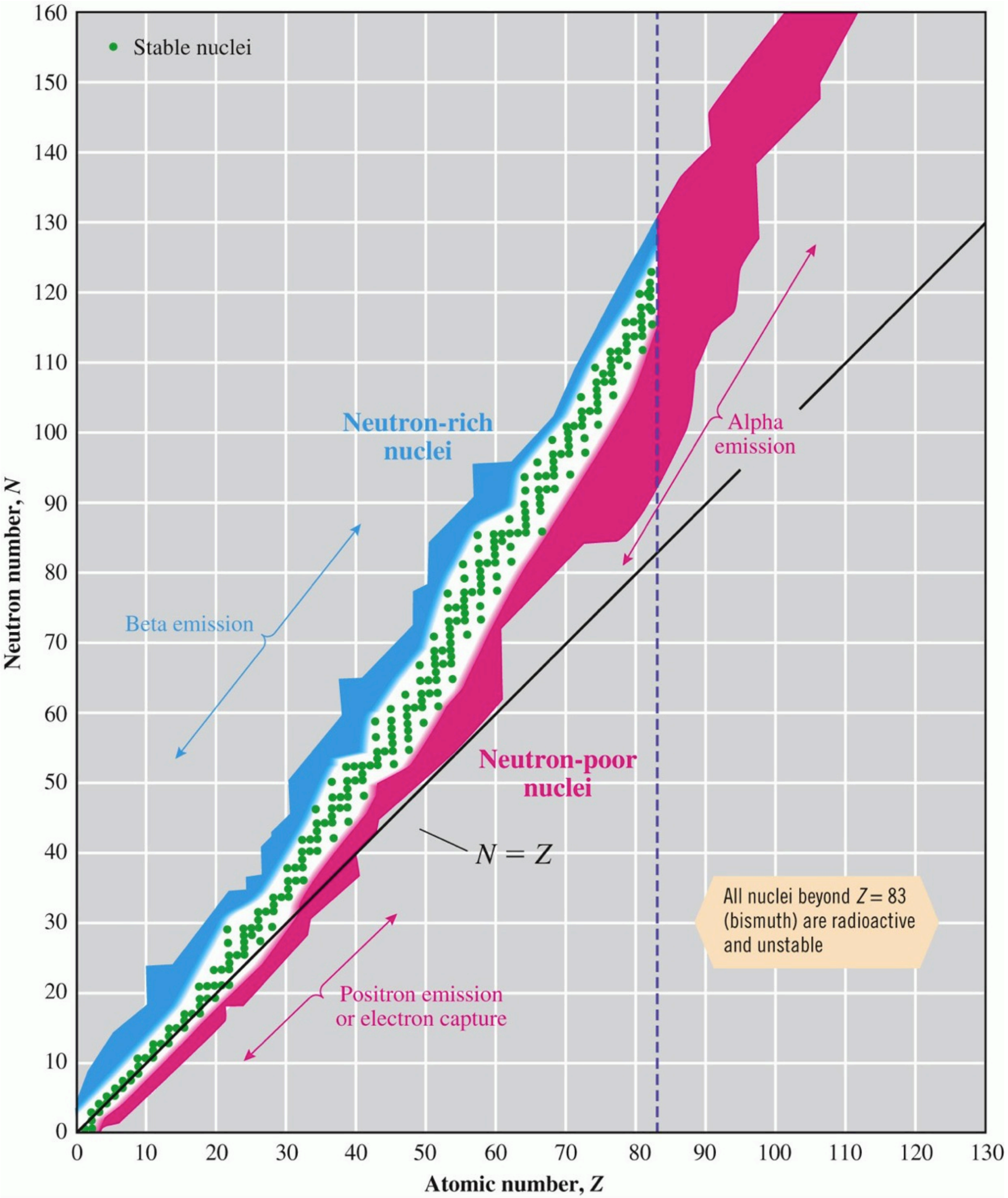


Figure 22-1 (10th edition)

Mass Deficiency

- There is a discrepancy between the *actual*, experimentally-measured mass of an atom and its *theoretical* mass (= sum of protons, neutrons, and electrons in that atom).

$$\boxed{\Delta m = (\text{masses of } p + n + e) - \text{actual mass of atom}}$$

- This *mass deficiency* (Δm) is < 0.15% for all naturally-occurring isotopes. Exception: H-1 at 0%
- Where did the “missing” mass go? It was transformed into energy according to Einstein’s famous equation:

$$\boxed{E = mc^2} \quad \text{OR} \quad \boxed{E = (\Delta m)c^2}$$

E = energy in joules, m = mass in kg, $c = 3.00 \times 10^8$ m/s

Masses of Protons, Neutrons, and Electrons

- *amu = atomic mass unit* = $^{1}/_{12}$ the mass of a carbon atom containing 6 protons and 6 neutrons (just remember it's a very small unit of mass)

proton	1.6726×10^{-27} kg	=	1.0073 amu
neutron	1.6749×10^{-27}	=	1.0087
electron	9.1092×10^{-31}	=	0.00054858

The mass of an electron is approximately 2000x smaller than that of a proton or neutron!

Nuclear Binding Energy

$$\boxed{E = (\Delta m)c^2}$$

- In this context, "*E*" in Einstein's equation is referred to as the *nuclear binding energy* = amount of energy that would be released if the nucleus were formed from initially separate protons, neutrons, and electrons

- Nuclides with the highest binding energies are the most stable.
  - Fe-56 is the most stable of all.

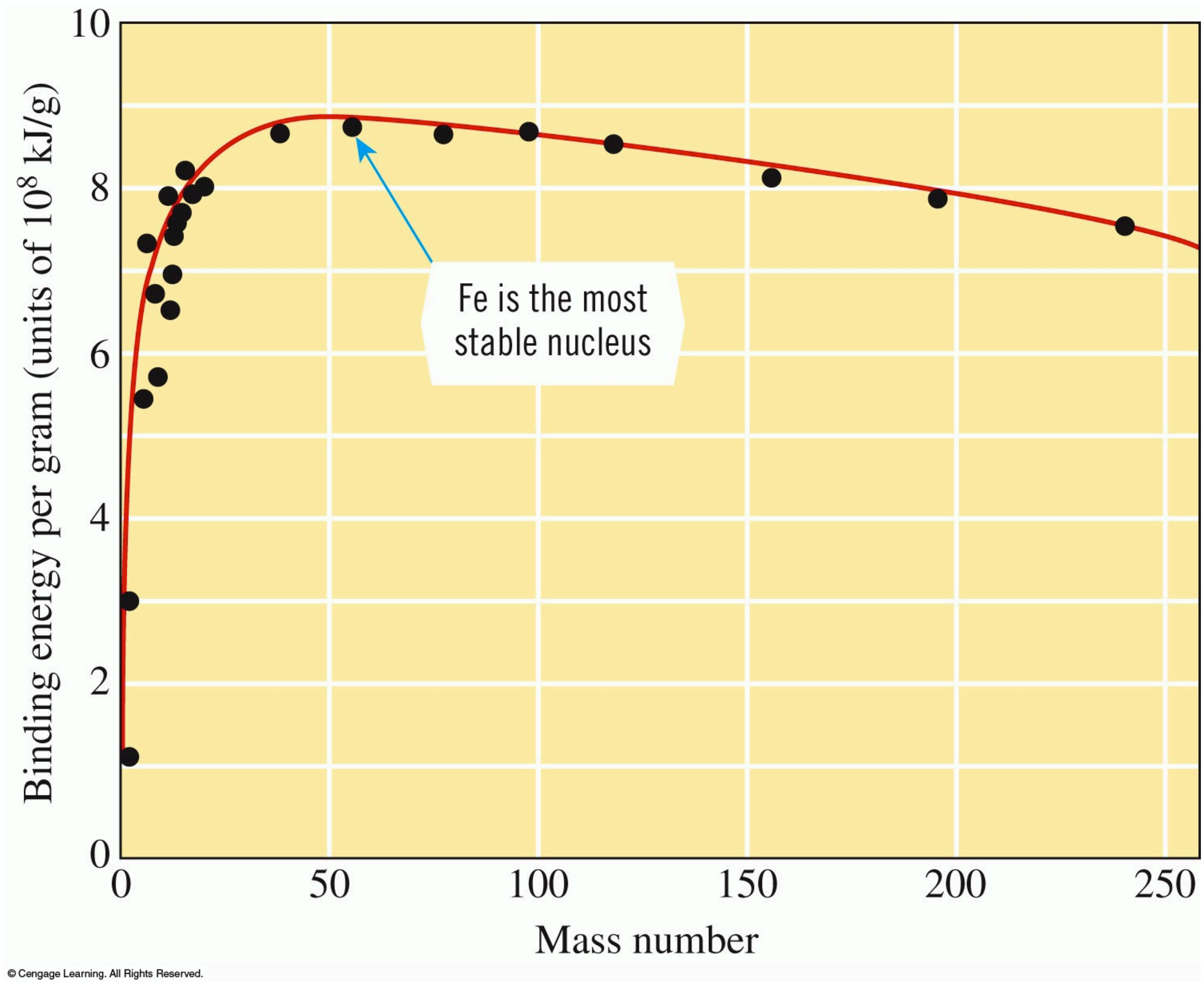


Figure 22-2 (10th edition)

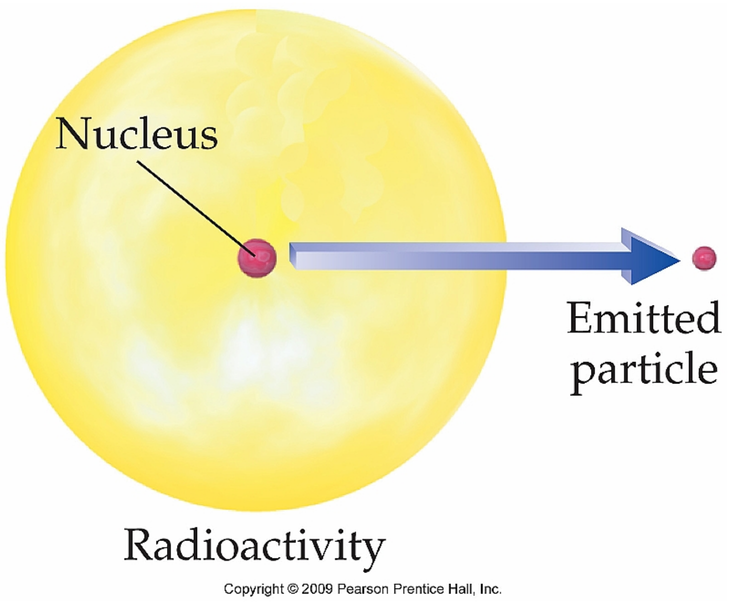
Practice 22.1

- The actual, experimentally-determined mass of a single Pd-108 atom is 1.7917×10^{-25} kg.
  a) Calculate the *mass deficiency* (Δm) in kg/atom for this isotope.
  b) What is the *nuclear binding energy* in kJ/mol for this isotope?

Radioactive Decay

Types of Radioactive Decay

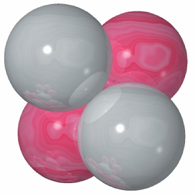
- *Radioactivity* = the tendency of an unstable nucleus to emit radiation
- There are several types:
  - alpha (α) emission
    - most common
  - beta (β) emission
  - positron emission
  - electron capture
  - gamma (γ) emission



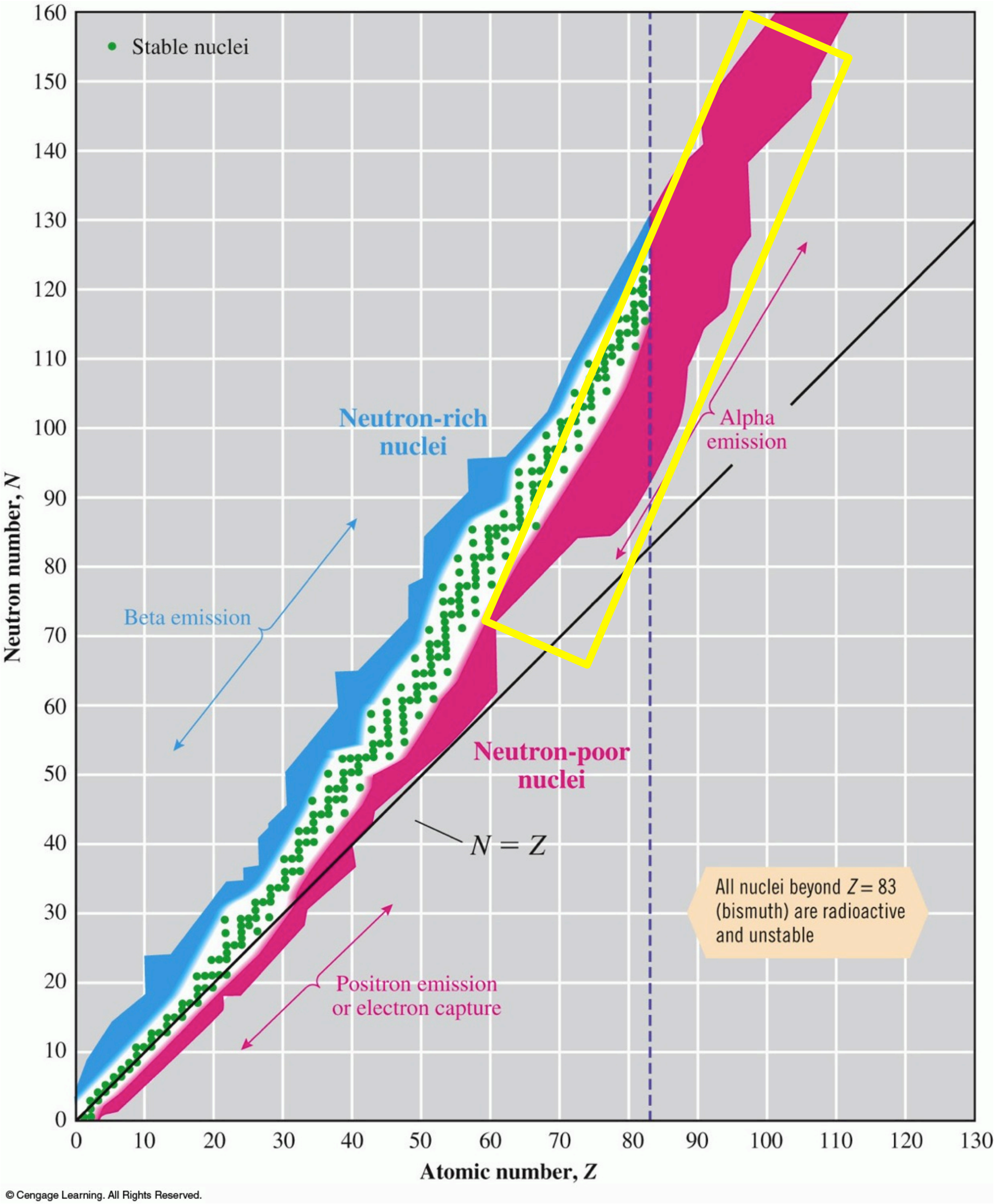
Alpha (α) Emission

- Results in emission of an *alpha particle*, which is simply a He nucleus.
  - Occurs in heavy, unstable nuclei like U-235 and Ra-226, in which *N*/*Z* is too small.

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



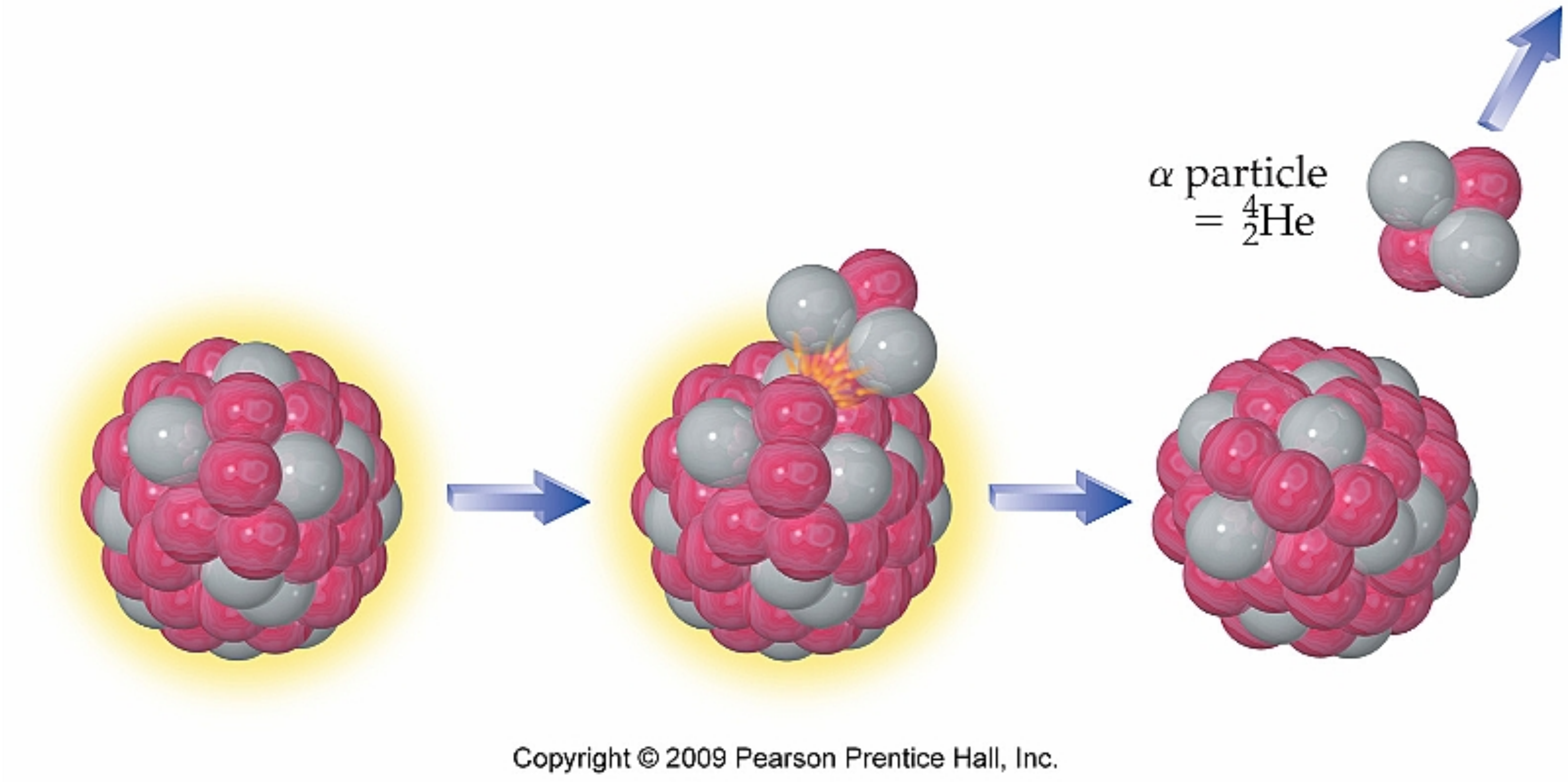
- Note that *atomic numbers* and *mass numbers* are balanced in a nuclear equation.



© Cengage Learning. All Rights Reserved.

Figure 22-1 (10th edition)

Alpha Emission



Beta (β) Emission

- Results in emission of a β particle, which is simply an electron.

$$ {}^{3}_{1}\text{H} \longrightarrow {}^{3}_{2}\text{He} + {}^{0}_{-1}\beta $$

- Occurs in the nucleus when a *neutron* is transformed into a *proton* <u>and</u> a β *particle*.

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

- Tends to occur when *N*/*Z* is too <u>large</u>.
  - Examples: P-32, H-3 (tritium)

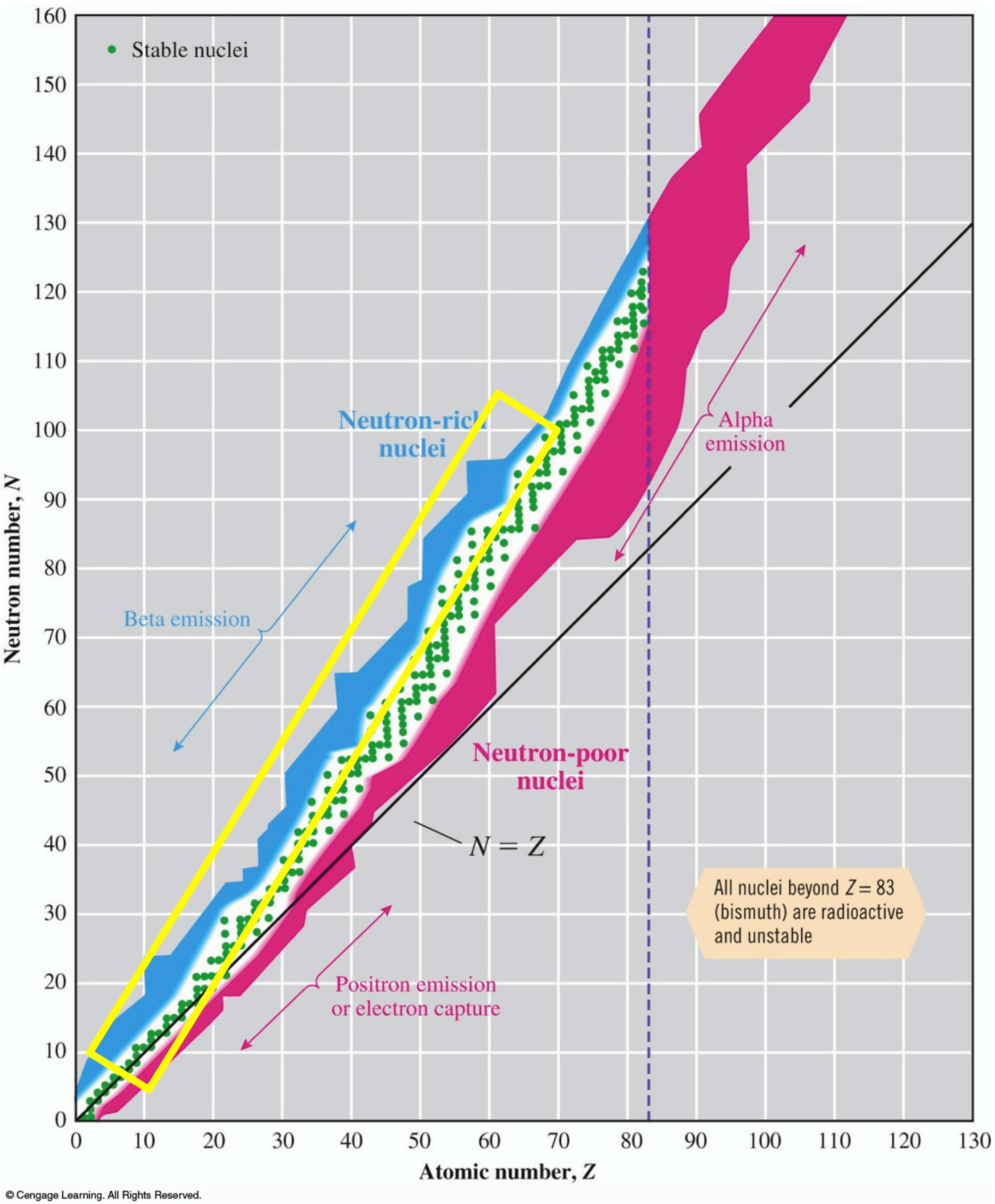
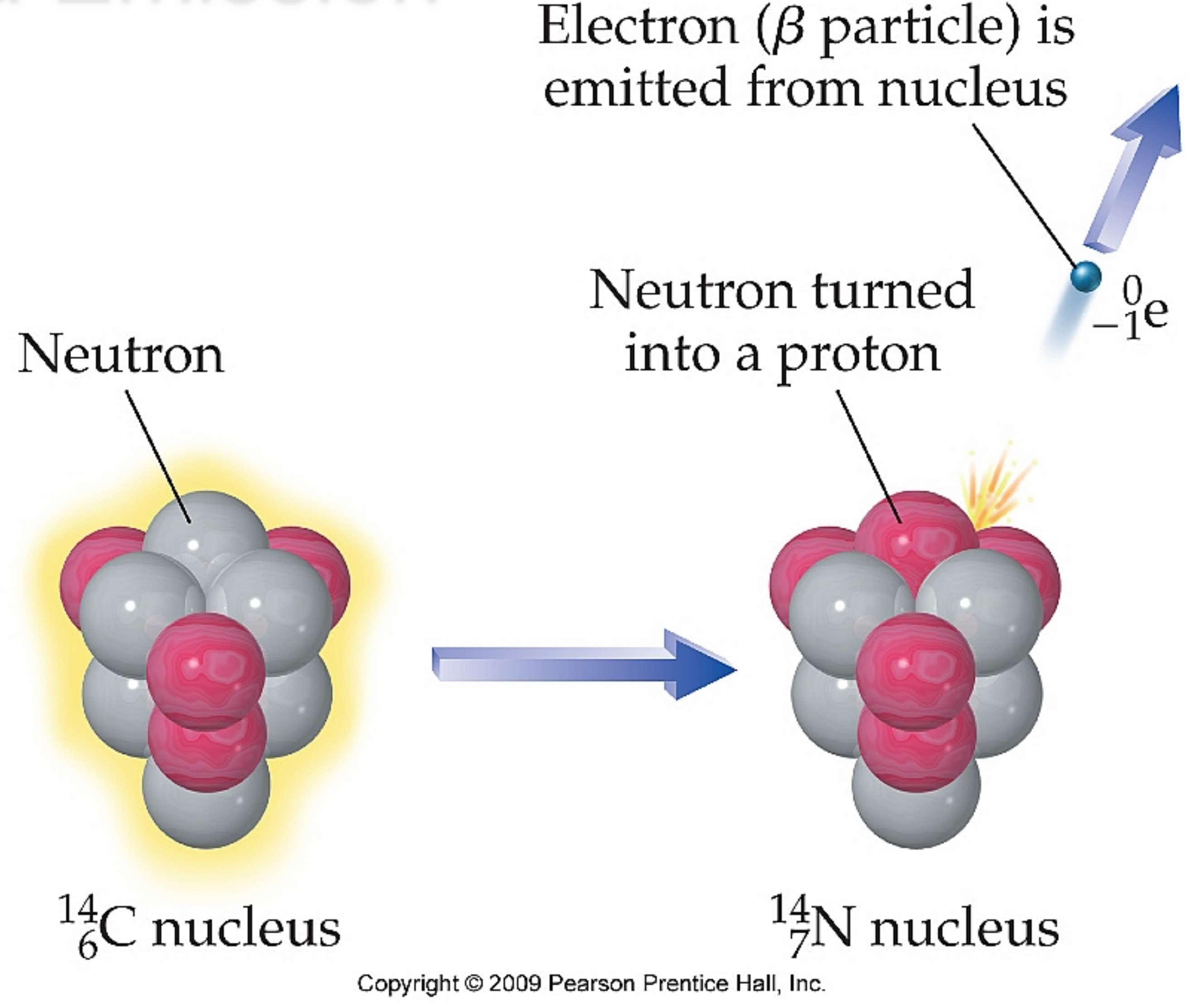


Figure 22-1 (10th edition)

Beta Emission



Positron Emission

- Results in emission of a *positron* ("positive electron"); the opposite effect of β emission.

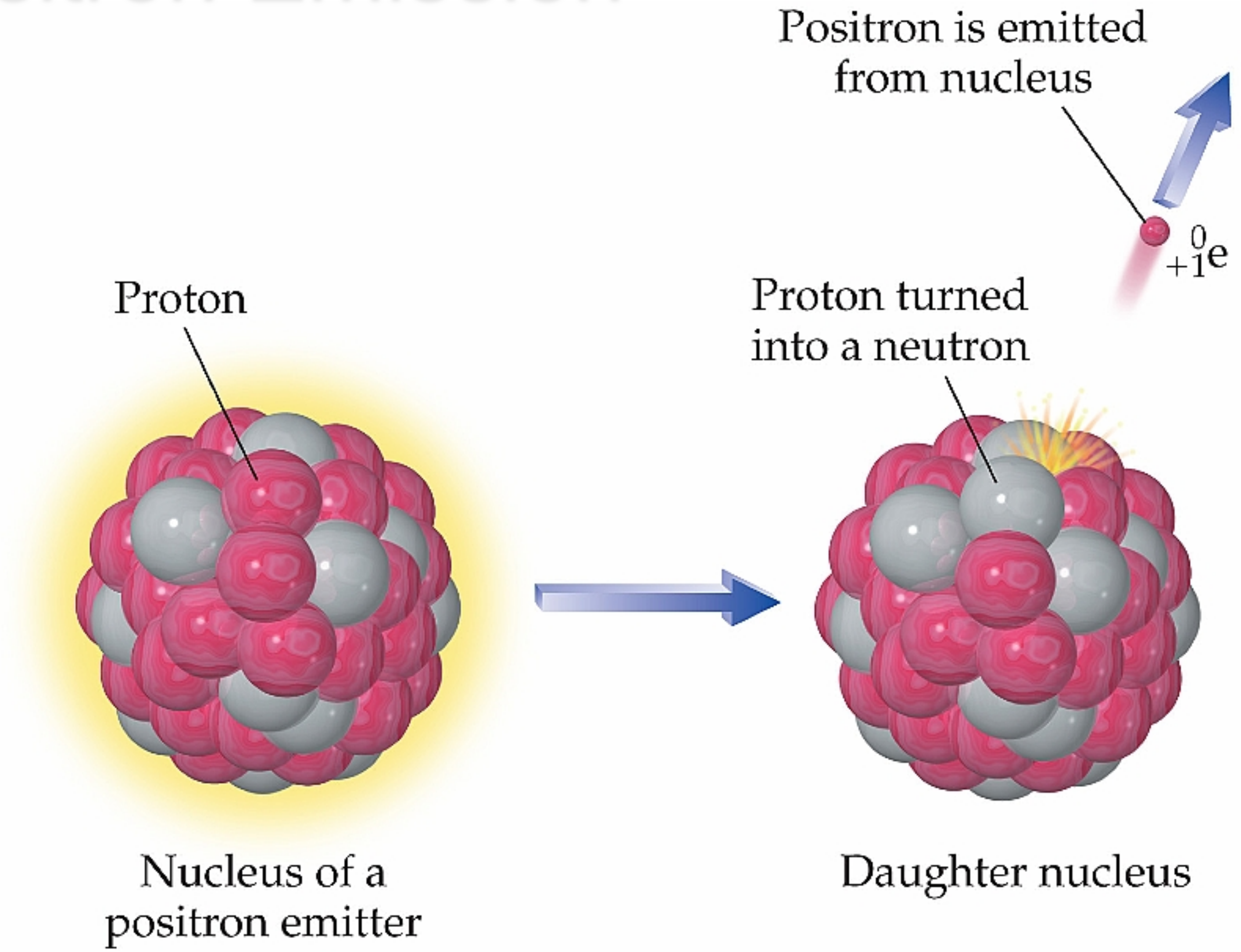
$$^{30}_{15}\mathrm{P} \longrightarrow ^{30}_{14}\mathrm{Si} + ^{0}_{+1}\beta$$

- Occurs in the nucleus when a *proton* is transformed into a *neutron* and *positron*.

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

- Tends to occur when *N*/*Z* is too small.

Positron Emission



Electron Capture

- An electron from the *K* shell (*n* = 1) is captured by the nucleus; note this is not the same as ionization!

$$ {}^{37}_{18}\mathrm{Ar} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{37}_{17}\mathrm{Cl} $$

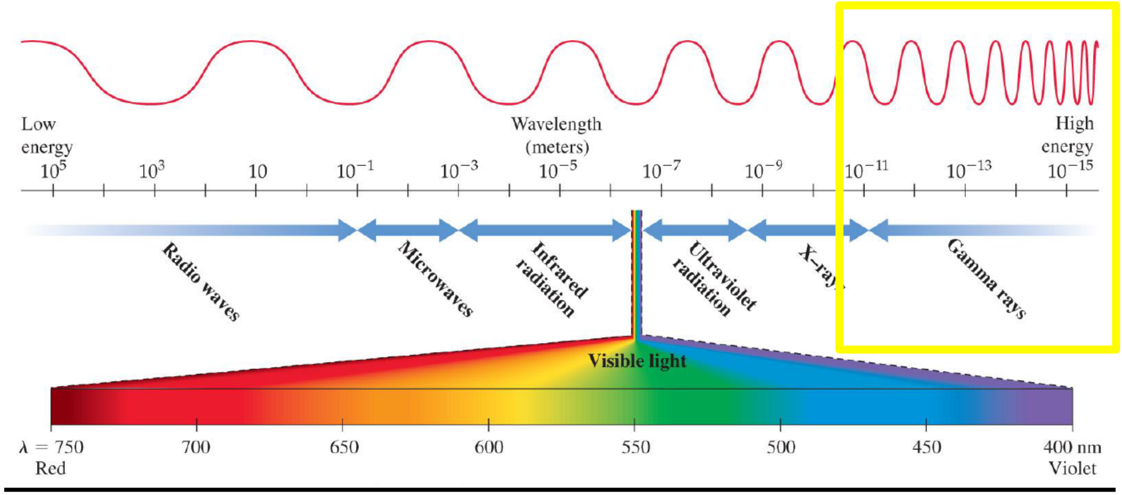
- Tends to occur when *N*/*Z* is too small.

Gamma (γ) Emission

- *Gamma emission* = emission of high energy radiation (no mass, no charge)

$$ {}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} + {}^{0}_{0}\gamma $$

- Occurs in conjunction with α or β emission.



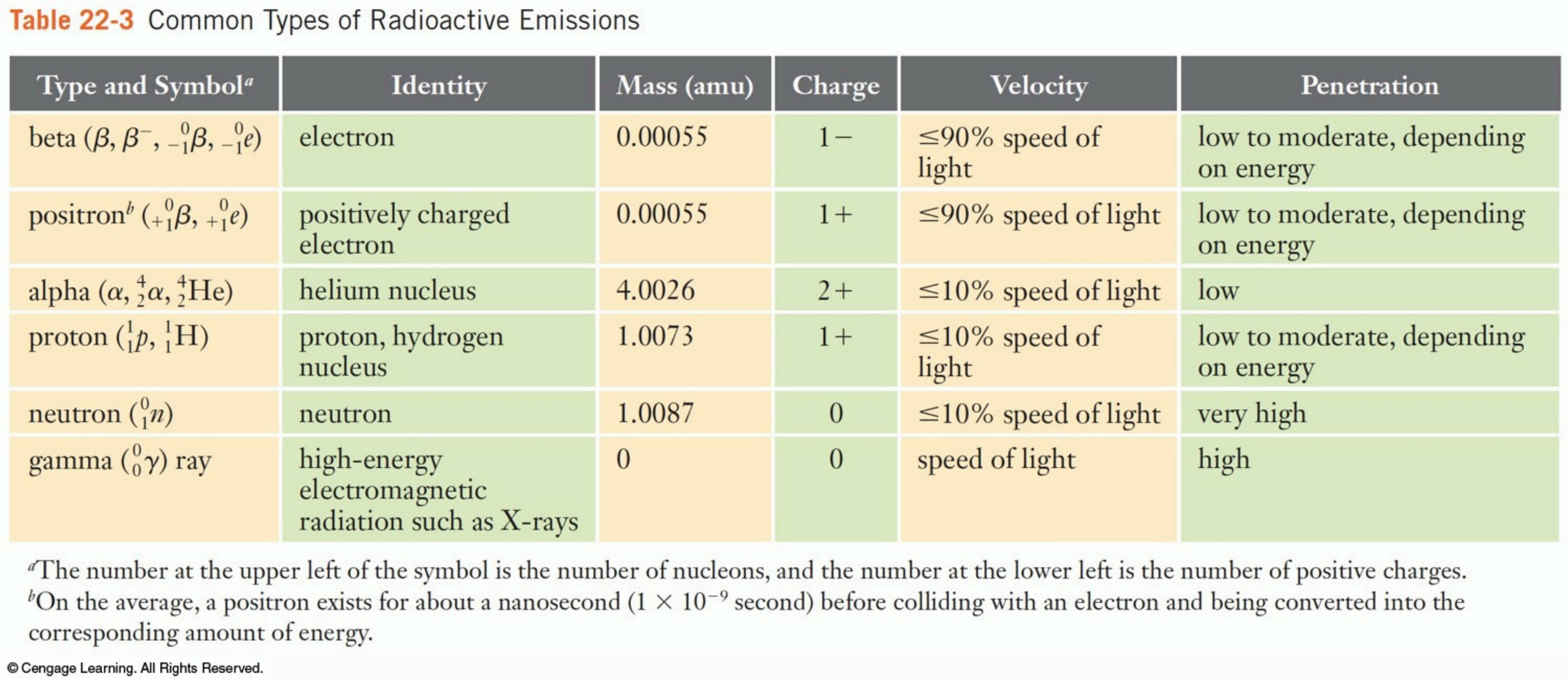


Table 22-3 Common Types of Radioactive Emissions

Type and Symbol[a]	Identity	Mass (amu)	Charge	Velocity	Penetration
beta (β, β^-, $_{-1}^{0}\beta$, $_{-1}^{0}e$)	electron	0.00055	1−	≤90% speed of light	low to moderate, depending on energy
positron[b] ($_{+1}^{0}\beta$, $_{+1}^{0}e$)	positively charged electron	0.00055	1+	≤90% speed of light	low to moderate, depending on energy
alpha (α, $_{2}^{4}\alpha$, $_{2}^{4}\mathrm{He}$)	helium nucleus	4.0026	2+	≤10% speed of light	low
proton ($_{1}^{1}p$, $_{1}^{1}\mathrm{H}$)	proton, hydrogen nucleus	1.0073	1+	≤10% speed of light	low to moderate, depending on energy
neutron ($_{1}^{0}n$)	neutron	1.0087	0	≤10% speed of light	very high
gamma ($_{0}^{0}\gamma$) ray	high-energy electromagnetic radiation such as X-rays	0	0	speed of light	high

[a] The number at the upper left of the symbol is the number of nucleons, and the number at the lower left is the number of positive charges.

[b] On the average, a positron exists for about a nanosecond (1×10^{-9} second) before colliding with an electron and being converted into the corresponding amount of energy.

How can we explain the differences in the "penetrating powers" of the various types of radiation? (final column to right)

Table 22-3 (10th edition)

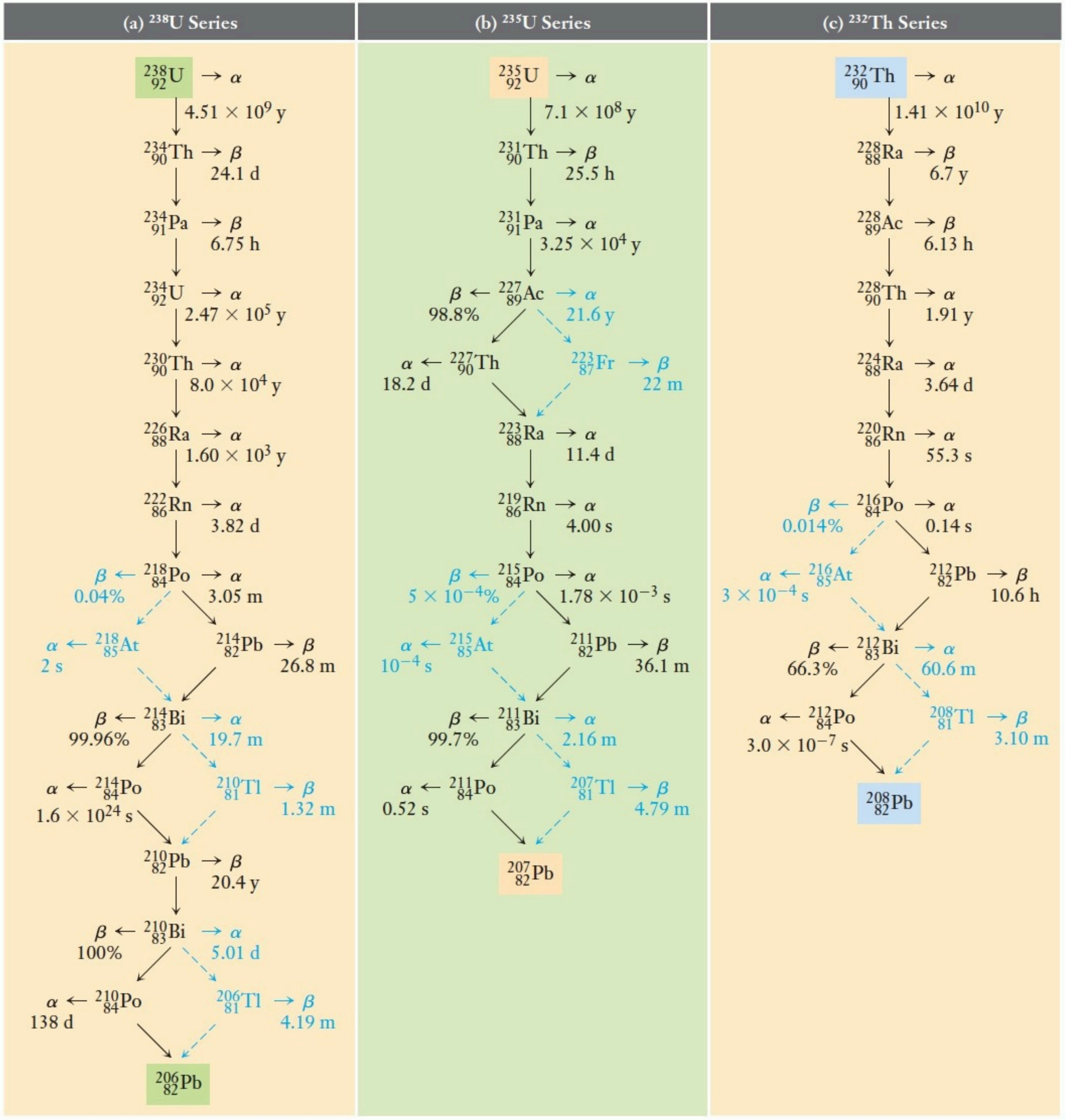
Practice 22.2

- Write a balanced nuclear equation for the following:
  a) Ti-45 decays by *positron emission*.
  b) Kr-81 decays by *electron capture*.

We'll write equations for alpha and beta emission in Practice 22.3.

Decay Series

Table 22-4 Emissions and Half-Lives of the Natural Radioactive Decay Series*



(a) ^{238}U Series

$^{238}_{92}\text{U} \to \alpha$
4.51×10^9 y
$^{234}_{90}\text{Th} \to \beta$
24.1 d
$^{234}_{91}\text{Pa} \to \beta$
6.75 h
$^{234}_{92}\text{U} \to \alpha$
2.47×10^5 y
$^{230}_{90}\text{Th} \to \alpha$
8.0×10^4 y
$^{226}_{88}\text{Ra} \to \alpha$
1.60×10^3 y
$^{222}_{86}\text{Rn} \to \alpha$
3.82 d
$\beta \leftarrow {}^{218}_{84}\text{Po} \to \alpha$
0.04% 3.05 m
$\alpha \leftarrow {}^{218}_{85}\text{At}$ $^{214}_{82}\text{Pb} \to \beta$
2 s 26.8 m
$\beta \leftarrow {}^{214}_{83}\text{Bi} \to \alpha$
99.96% 19.7 m
$\alpha \leftarrow {}^{214}_{84}\text{Po}$ $^{210}_{81}\text{Tl} \to \beta$
1.6×10^{24} s 1.32 m
$^{210}_{82}\text{Pb} \to \beta$
20.4 y
$\beta \leftarrow {}^{210}_{83}\text{Bi} \to \alpha$
100% 5.01 d
$\alpha \leftarrow {}^{210}_{84}\text{Po}$ $^{206}_{81}\text{Tl} \to \beta$
138 d 4.19 m
$^{206}_{82}\text{Pb}$

(b) ^{235}U Series

$^{235}_{92}\text{U} \to \alpha$
7.1×10^8 y
$^{231}_{90}\text{Th} \to \beta$
25.5 h
$^{231}_{91}\text{Pa} \to \alpha$
3.25×10^4 y
$\beta \leftarrow {}^{227}_{89}\text{Ac} \to \alpha$
98.8% 21.6 y
$\alpha \leftarrow {}^{227}_{90}\text{Th}$ $^{223}_{87}\text{Fr} \to \beta$
18.2 d 22 m
$^{223}_{88}\text{Ra} \to \alpha$
11.4 d
$^{219}_{86}\text{Rn} \to \alpha$
4.00 s
$\beta \leftarrow {}^{215}_{84}\text{Po} \to \alpha$
5×10^{-4}% 1.78×10^{-3} s
$\alpha \leftarrow {}^{215}_{85}\text{At}$ $^{211}_{82}\text{Pb} \to \beta$
10^{-4} s 36.1 m
$\beta \leftarrow {}^{211}_{83}\text{Bi} \to \alpha$
99.7% 2.16 m
$\alpha \leftarrow {}^{211}_{84}\text{Po}$ $^{207}_{81}\text{Tl} \to \beta$
0.52 s 4.79 m
$^{207}_{82}\text{Pb}$

(c) ^{232}Th Series

$^{232}_{90}\text{Th} \to \alpha$
1.41×10^{10} y
$^{228}_{88}\text{Ra} \to \beta$
6.7 y
$^{228}_{89}\text{Ac} \to \beta$
6.13 h
$^{228}_{90}\text{Th} \to \alpha$
1.91 y
$^{224}_{88}\text{Ra} \to \alpha$
3.64 d
$^{220}_{86}\text{Rn} \to \alpha$
55.3 s
$\beta \leftarrow {}^{216}_{84}\text{Po} \to \alpha$
0.014% 0.14 s
$\alpha \leftarrow {}^{216}_{85}\text{At}$ $^{212}_{82}\text{Pb} \to \beta$
3×10^{-4} s 10.6 h
$\beta \leftarrow {}^{212}_{83}\text{Bi} \to \alpha$
66.3% 60.6 m
$\alpha \leftarrow {}^{212}_{84}\text{Po}$ $^{208}_{81}\text{Tl} \to \beta$
3.0×10^{-7} s 3.10 m
$^{208}_{82}\text{Pb}$

*Abbreviations are y, year; d, day; m, minute; and s, second. Less prevalent decay branches are shown in blue.

Table 22-4 (10th edition)

Practice 22.3

- Write a partial decay series for Th-232 undergoing the following sequential decays: α, β

Kinetics of Nuclear Decay: Half-Life Calculations

Decay Rate and Half-Life

- Radioactive decay follows **first**-order kinetics; so, let's revisit the first-order IRE from Chapter 16:

$$\boxed{\begin{array}{l} \text{rate of decay} = k(\text{A}) \\ \ln(\text{A}_0 / \text{A}_t) = kt \\ t_{1/2} = 0.693 / k \end{array}}$$

"a" is not shown because a = 1 for all nuclear processes

- "A" can represent *mass*, *moles*, *disintegrations per minute*, or other convenient units.

- *Half-life* = the time required for one half of the radioactive atoms in a sample to decay

TABLE 17.1 Selected Nuclides and Their Half-Lives

Nuclide	Half-Life	Type of Decay
${}^{232}_{90}\mathrm{Th}$	1.4×10^{10} yr	alpha
${}^{238}_{92}\mathrm{U}$	4.5×10^{9} yr	alpha
${}^{14}_{6}\mathrm{C}$	5730 yr	beta
${}^{220}_{86}\mathrm{Rn}$	55.6 s	alpha
${}^{219}_{90}\mathrm{Th}$	1.05×10^{-6} s	alpha

Practice 22.4

a) How many half-lives have elapsed if only 12.5% of an original radioactive sample remains?

b) If 160. mg of Tc-99 ($t_{1/2}$ = 6.0 hr) is administered for medical diagnosis, what mass of the nuclide remains after 72.0 hr?

c) If an Fe-59 sample has an initial activity of 800 dpm, how many days will it take for the activity to drop to 25 dpm? The half-life of Fe-59 is 45 days. (dpm = disintegrations/min)

Application: Radiocarbon Dating

- C-14 is continuously produced in the upper atmosphere when cosmic neutrons are "captured" by N-14:

$$^{14}_{7}\mathrm{N} + ^{1}_{0}\mathrm{n} \longrightarrow ^{14}_{6}\mathrm{C} + ^{1}_{1}\mathrm{H}$$

- This C-14 is taken up by respiring organisms (as CO_2) and reaches an equilibrium in the tissues; when the organism dies, the C-14 decays predictably.
- By measuring the decay rate and using the IRE, the organism (or its tissues) can be dated.

Nuclear Fission and Fusion

Nuclear Fission

- Nuclei with $Z > 80$ can “split” or undergo *fission*.
- The process releases an enormous amount of energy.
- In a highly controlled process, U-235 nuclei are bombarded with neutrons to make the nuclei unstable and cause them to “split.” The decay releases neutrons that, in turn, collide with more U-235 nuclei and induce more splitting. The result is a *nuclear chain reaction*.
    - ➢ Basis of nuclear energy production; atomic bomb

Nuclear Chain Reaction

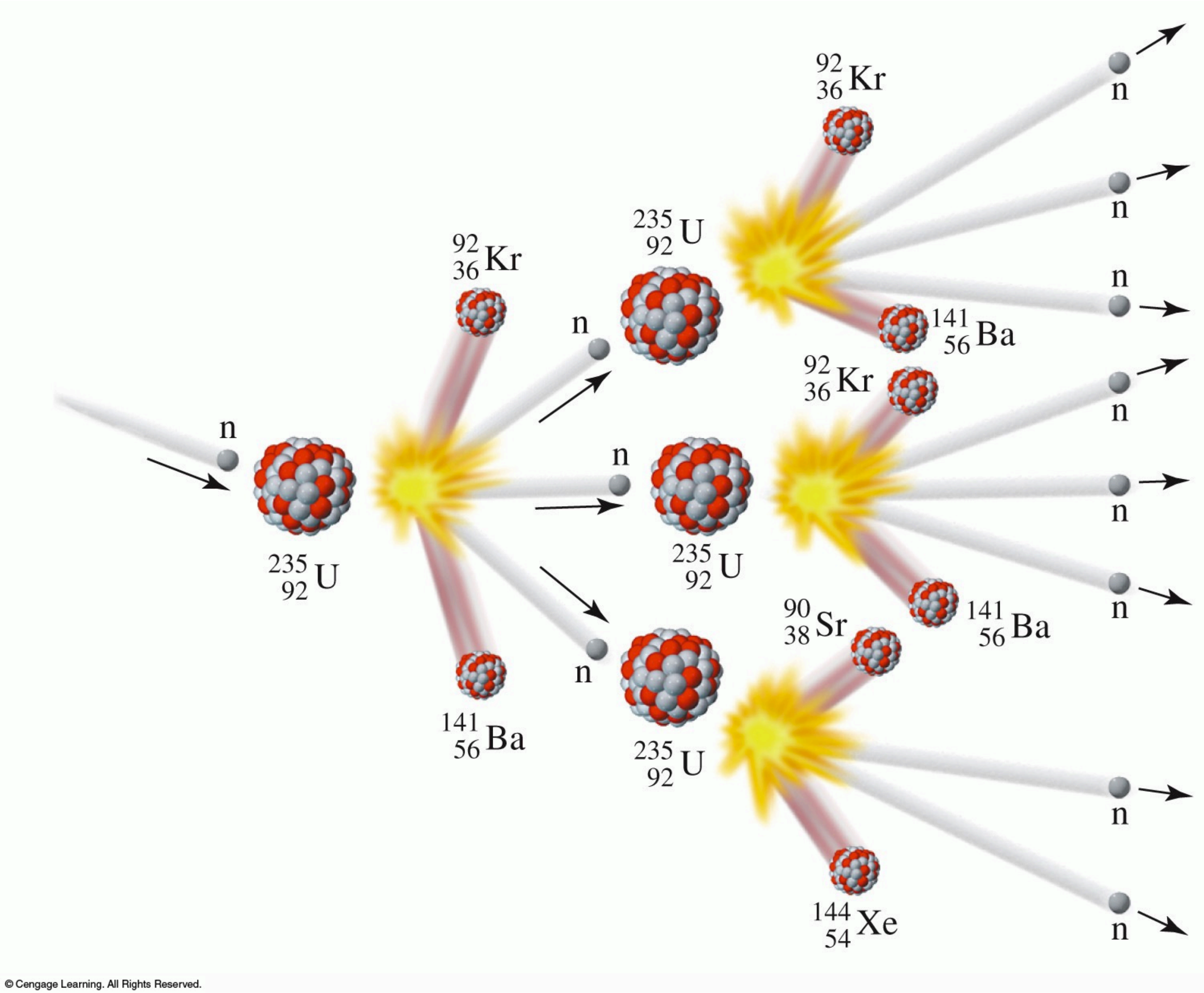
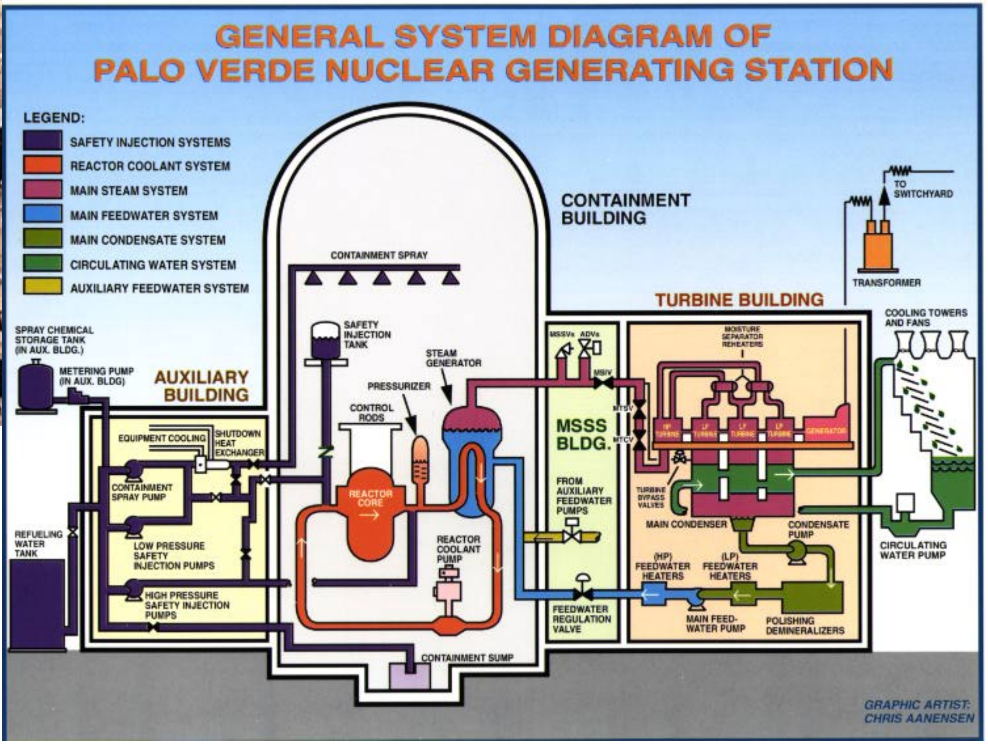


Table 22-12 (10th edition)

Nuclear Energy → Electricity

nuclear energy → thermal energy → kinetic energy of steam → rotational energy spins turbine → electrical energy (electricity)



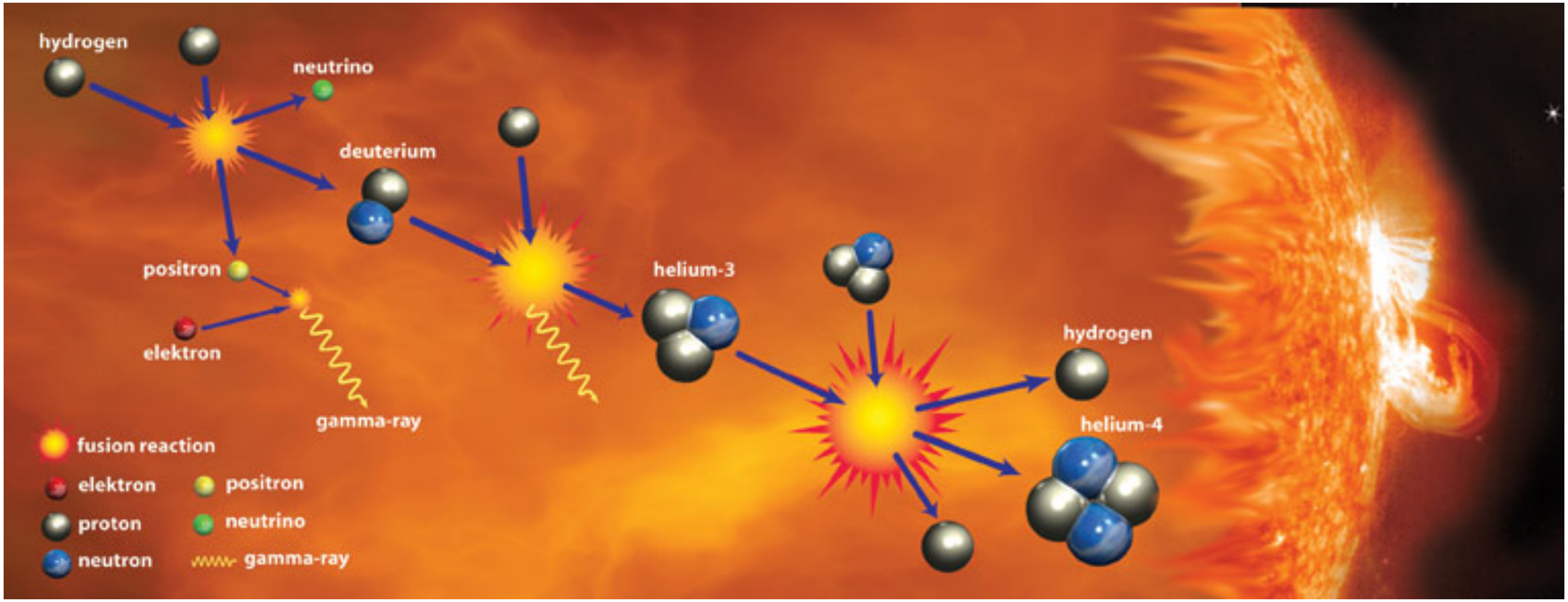
Nuclear Fusion

- Smaller nuclei fuse to produce larger nuclei in the sun:

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 1.7 \times 10^{19}\ kJ/mol$$

- Much of the energy is released as heat; temperature of the sun is ~ 4×10^{7} K
- The remaining energy is emitted as UV, X-rays, visible light, IR, microwaves, and radio waves.
- Can we achieve “cold” fusion on earth?

Nuclear Fusion Occurs in the Sun



http://www.scienceinschool.org/repository/images/issue3_fusion1_large.jpg

Other Exciting Applications of Nuclear Technology

Radioisotopes in Medicine

- I-131 is used to diagnose and treat thyroid disease.

- Tc-99 is the most commonly used isotope in nuclear imaging.

- Radioactive "implants" to treat tumors (brachytherapy):
  - Ru-106
  - Cs-137
  - Co-60 *among others...*